REDUCING THE INTERFACIAL TENSION OF MAGNETIC SURFACTANTS IN MAGNETIC FIELDS

by
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ABSTRACT

This thesis discusses the theory, experimental research methods, and findings of the effects that magnetic fields have on the interfacial tension of magnetic surfactant solutions. Analyzing how magnetic fields affect the properties of magnetic surfactants, including interfacial tension, is the first step to creating low energy, magnetic field induced separations to address the problem of growing energy demands for chemical and biological separations [1]. Surfactants are organic structures that contain both a hydrophilic head group and a hydrophobic tail, which aggregate toward the interface of solutions and decrease the interfacial tension until the critical micelle concentration is reached. Magnetic surfactants are created by replacing the counterion of a non-magnetic surfactant with a metal-counterion. Theoretically, when magnetic surfactants are exposed to a magnetic field the monomers will tightly align, allowing for more monomers at the interface and resulting in a decrease in surface tension. To test this theory, magnetic surfactants were exposed to two different magnetic fields produced by a solenoid magnetic field and a set of two permanent magnets parallel to the surfactants. $C_{38}H_{84}N_2Br_2CoC_{12}$, $C_{19}H_{42}NBrDyC_{13}$, and $C_{19}H_{42}NBrFeC_{13}$ were the surfactants which at several concentrations were suspended into the magnetic fields as droplets from needles, and the pendant drop method was used to analyze the dimensions of the droplets and calculate the surface tension. The surface tension decreased as the surfactant concentrations increased with a slight dip and rise in surface tension. Considering the surfactants were not completely pure solutions, this was expected, as previous research has shown that the interfacial tension of surfactants can display a slight dip and rise near their critical micelle concentration (CMC) values [8]. Some data points followed the hypothesis, while others showed trends opposing the

hypothesis. Some data points showed a general trend between surface tension and magnetic field strength. Due to the large range in standard deviation values, the inconsistent trends, and the possible presence of impure surfactant solutions, the research would benefit from taking data on ten to fifteen droplets for each concentration, using more purified surfactants, and determining the surface tension at more concentrations past the CMC.

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1 INTRODUCTION

1.1 Surfactants

Surfactants are organic compounds characterized by having amphipathic properties, meaning they possess both hydrophilic and hydrophobic regions in their structures. More specifically, surfactants have a hydrophilic head along with a hydrophobic tail. The interactions between the solvent, which is usually water, and the hydrophobic tails of surfactant monomers are unfavorable and increase the energy of a system. Since the hydrophobic tails and water interactions are unfavorable, the monomers aggregate toward the interface of the solution with the hydrophobic tails arranged toward the surface to decrease the system's energy. The aggregation of hydrophobic tails at the interface disrupts the hydrogen bonding of the water molecules, creating the interfacial tension, which is decreased. More surfactant monomers at the interface result in more disruptions of hydrogen bonding at the interface and an even lower interfacial tension. The surfactant monomers will adsorb onto the surface until the critical micelle concentration (CMC) of the particular surfactant is reached. After the CMC is reached, adsorption is limited, as the surfactant forms micelles in the system in order to increase the entropy of the system. Critical micelle concentration is based on the specific properties of the surfactant, including the surfactant chain length. The favored micelle formation, resulting from an increase in entropy, is shown in Figure 1-1.

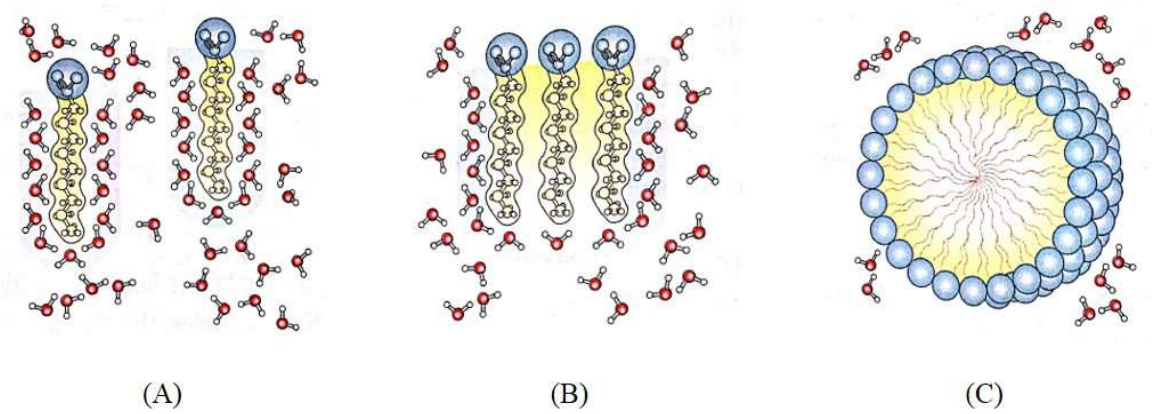

Figure 1-1. Micelle formation resulting from an increase in entropy.
A) Each lipid molecule forces surrounding H_2O molecules to become highly ordered. B) Only lipid portions at the edge of the cluster force the ordering of water. Fewer H_2O molecules are ordered, and entropy is increased. C) All hydrophobic groups are sequestered from water; ordered shell of H_2O molecules is minimized, and entropy is further increased. [2]

There are four types of head groups that surfactants can have anionic, cationic, zwitterionic, and nonionic. Magnetic surfactants can be created by replacing the head group of a non-magnetic surfactant with a metal. In this research, the non-magnetic surfactant hexadecyltrimethylammonium bromide (C-TAB), with the chemical formula $C_{19}H_{42}BrN$, was used as the control surfactant. The magnetic surfactants were synthesized from C-TAB with the following head groups: cobalt, dysprosium, and iron. These magnetic surfactants are abbreviated C-TACo, C-TADy, and C-TAFe, respectively. The chemical formula for C-TACo is $C_{38}H_{84}N_2Br_2CoCl_2$. The chemical formula for C-TADy is $C_{19}H_{42}NBrDyCl_3$ and for C-TAFe is $C_{19}H_{42}NBrFeCl_3$. The chemical structure for C-TAB is shown in Figure 1-2.

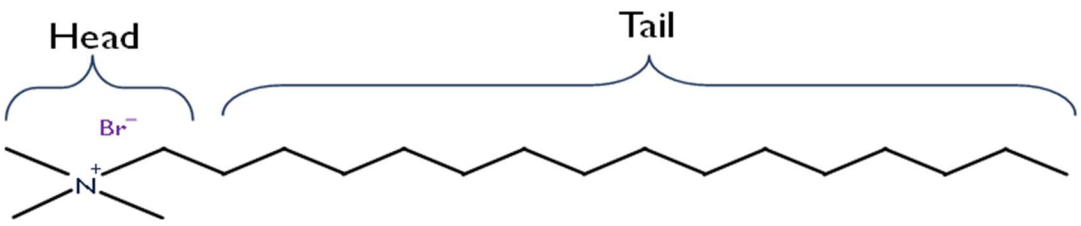

Figure 1-2. The chemical structures for non-magnetic surfactant C-TAB.

1.2 Theory behind Surface Tension of Magnetic Surfactants in Magnetic Fields

It is theorized that exposure to a magnetic field induces a tight alignment of the magnetic surfactant monomers at the interface of the solution, as the magnetic field pulls the monomers toward the magnet. If a tight alignment of magnetic surfactant monomers at the interface is present, more monomers aggregate toward the interface. The increase in monomer aggregation at the interface results in a greater disruption in hydrogen bonding and a decrease in interfacial tension. This is represented in Figure 1-3.

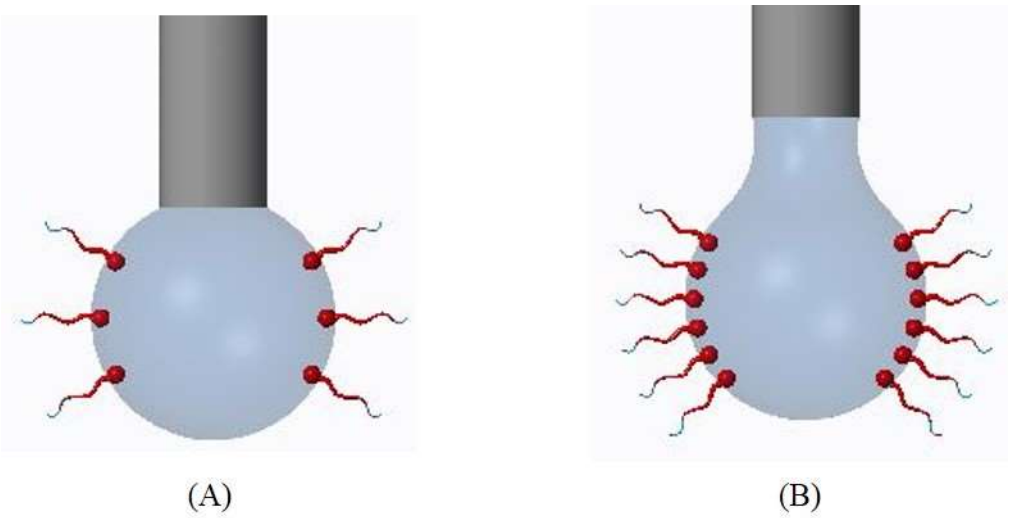

Figure 1-3. Monomer aggregation at the interface.
(A) The monomer arrangement of magnetic surfactants at the interface outside of a magnetic field. (B) The monomer arrangement with a tight alignment of magnetic surfactants at the interface inside a magnetic field.

1.3 Measuring Surface Tension

There are several methods currently used in laboratories to measure surface tension of solutions such as, Wilhelmy plate, Du Nouy ring, pendant drop, sessile drop, drop volume/weight, maximum bubble pressure, growing drop/bubble, oscillating jet, and pulsating bubble [3]. The pendant drop method was used to measure interfacial tension in this experimental research because it is easily incorporated into a magnetic field and only requires a pendant drop's dimensions, which can be recorded with a low-magnification

lens camera [3]. Also, since a needle can produce the droplet and the needle tip can be covered using a glass, capillary tube, there is no interaction and interference of the magnetic field with the needle. Although this method can easily be incorporated into a magnetic field, it requires extreme cleanliness of the needle and a careful, consistent procedure to create reproducible results. Two dimensions are needed to calculate the interfacial tension from the pendant drop. The two dimensions are equatorial diameter, D, and the diameter, d, at the distance, D, from the bottom of the drop [3]. The pendant drop method requires a USB digital microscope to capture images of the droplets. Computer software can be used to measure D and d of each droplet. For this particular research, the Olympus Stream Essentials Desktop 1.9.4 Full was used to measure the D and d in terms of pixels and, then, converted to measurement units based on the software. These dimensions are shown in Figure 1-4.

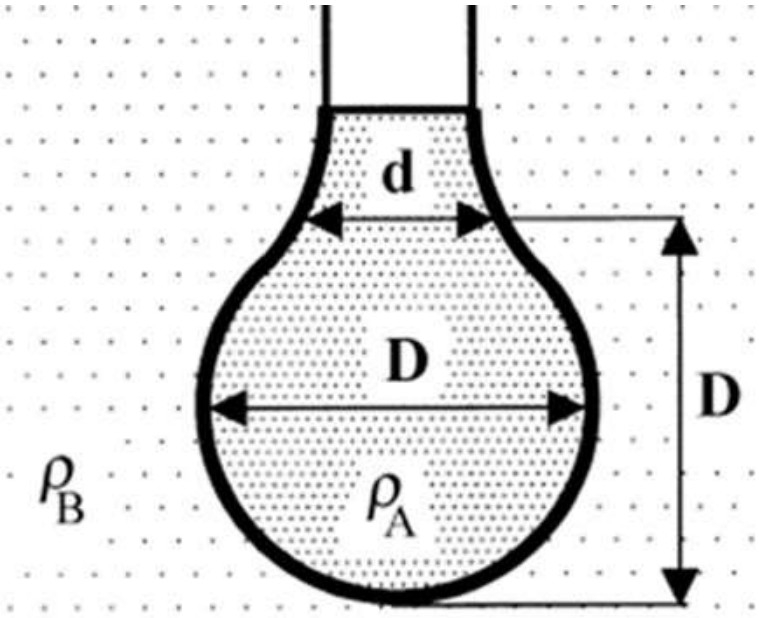

Figure 1-4. The dimensions of a droplet used to find the surface tension using the pendant drop method [3].

An example of these dimensions measured for a droplet from the laboratory can be seen in Figure 1-5.

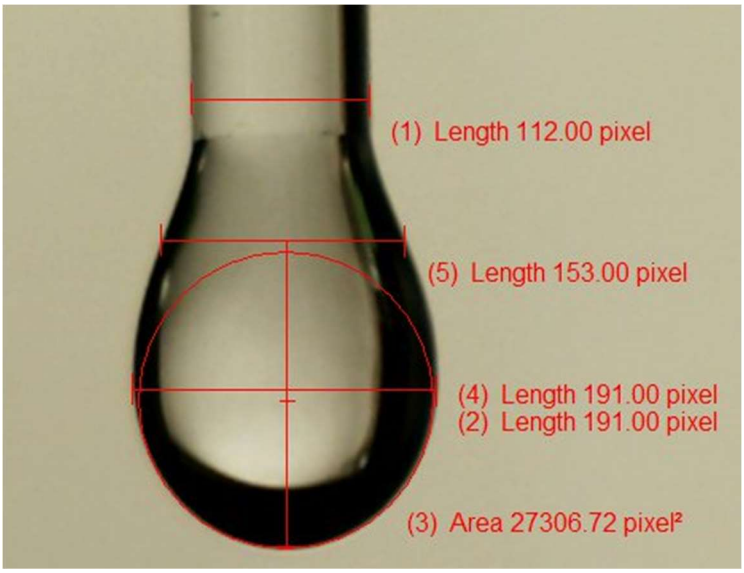

Figure 1-5. An example of a droplet measured with the Olympus Stream Essentials Desktop 1.9.4 Full Software.

The interfacial tension can be found using Equation 1.1.

$$\text{Equation 1.1} \qquad \gamma = \frac{\Delta\rho g D^2}{H}$$

γ is the interfacial tension of the solution, Δρ is the density difference between the solution and the surrounding air in which the solution is suspended, g is the gravitational constant due to acceleration, D is the equatorial diameter of the droplet, and H is the shape dependent parameter, which is dependent upon the shape factor, S. The shape factor is defined by Equation 1.2.

$$\text{Equation 1.2} \qquad S = \frac{d}{D}$$

d is the diameter of the droplet at the distance, D, from the bottom to the top of the droplet [3]. The shape dependent parameter can be calculated using the following empirical formula shown in Equation 1.3.

Equation 1.3 $$\frac{1}{H} = \frac{B_4}{S^a} + B_3S^3 - B_2S^2 + B_1S - B_0$$

B_1, B_2, B_3, B_4, and a are empirical constants for different ranges of S. These values are shown in Table 1-1.

Table 1-1. Empirical constants for shape dependent parameter [3].

Range of S	a	B_4	B_3	B_2	B_1	B_o
0.401-0.46	2.56651	0.3272	0	0.97553	0.84059	0.18069
0.46-0.59	2.59725	0.31968	0	0.46898	0.50059	0.13261
0.59-0.68	2.62435	0.31522	0	0.11714	0.15756	0.05285
0.68-0.90	2.64267	0.31345	0	0.09155	0.14701	0.05877
0.90-1.00	2.84636	0.30715	-0.69116	-1.08315	-0.18341	0.2097

With equation 1.1 and all of the known variables, the interfacial tension for each droplet can be calculated.

1.4 Previous Research

Previously, the surface tension of the surfactants CTAFe and CTADy was measured over a permanent magnet, as shown in Figure 1-6.

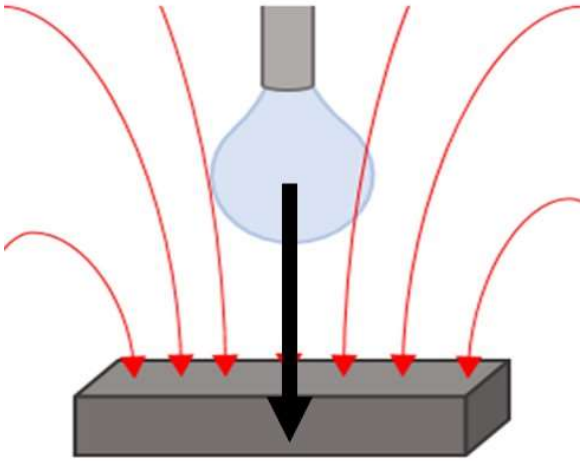

Figure 1-6. Attraction to magnetic surfactant monomers caused by a permanent magnet. The magnet field lines produced by a permanent magnet shown in red. The overall increase in force, shown in black, toward the permanent magnet as a result of an attraction to magnetic surfactant monomers in the droplet [4].

The surface tension of the magnetic surfactants decreased when the surfactants were exposed to the permanent magnet compared to when they were not [4]. Since the permanent magnetic field has an attraction to the magnetic surfactant monomers, the attraction could have created an overall increase in the net force pulling the droplet down toward the magnet in the direction of gravity. This would have elongated the droplet's shape and could have been the cause of the decreased surface tension. Since it was unclear whether or not the decreased surface tension was the result of the magnetic field's attraction to the magnetic surfactant monomers or an induced alignment, two other magnets, the solenoid magnet and the two permanent magnet apparatuses, were used to investigate the hypothesis. The magnetic field lines that these two types of magnets produce are seen in Figure 1-7.

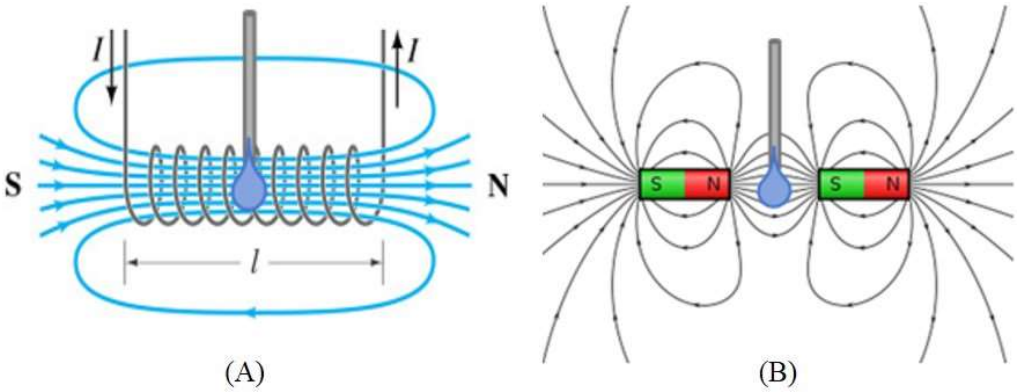

Figure 1-7. Magnetic field lines of solenoid and permanent magnets.
(A) The magnetic field lines in relationship to a droplet incorporated into a solenoid magnet [5]. (B) The magnetic field lines in relationship to a droplet incorporated in between two permanent magnets [6].

From Figure 1-7 (A) and (B), the magnetic field lines are parallel in relationship to the incorporated droplet. By having magnetic field lines parallel to the incorporated droplet, the magnetic field does not pull the droplet downward in the direction of gravity. Therefore, if the surface tension of the magnetic surfactants decreases when they are

incorporated into a parallel magnetic field, an induced alignment of monomers occurs. If the surface tension increases, indicative of no induced alignment of monomers, the magnetic field only has an attraction to the monomers and pulls the droplet in the direction of the field. The parallel magnetic fields pull the droplet outward, making the shape of the droplet shorter and more round, which increases the surface tension of the droplet.

2 EXPERIMENTAL

2.1 Equipment

Weigh paper, a metal spatula, and a scale were all used to measure the mass of solid surfactant needed. A 250 mL PYREX® volumetric flask was employed to mix the solid surfactant and deionized water to make the highest concentrations of the surfactants. A 100 mL PYREX® graduated cylinder and 100-1000 µL Finn pipette were utilized to extract the correct amount of the concentrated surfactant for each dilution. To make each diluted surfactant solution, a 50 mL PYREX© Erlenmeyer flask was used, and Fischer laboratory tape was applied to label each of the surfactant solutions. A Hamilton brand gastight 1000 series syringe with a 19 gauge blunt ended needle was utilized to suspend the surfactant droplets within the parallel magnetic field. Glass capillary tubes were placed over the metal needle tip and held in place with vacuum grease. For loading each solution into the syringe, as well as storage, small vial tubes were used, and Kimwipes® were applied to clean the external tip of the needle. A ring stand and clamps suspended the syringe and needle in the parallel magnetic field, and finger nail polish marked the ring stand and needle for consistency. A lamp was arranged behind the backdrop of the parallel magnetic field to make the droplet images brighter and more distinct. A solenoid magnet, containing a copper coil and a hole in the middle, in which the needle was inserted, was employed. For the solenoid magnet, a voltage and current source provided the parallel magnetic field with varying magnetic field strengths. For the two permanent magnets, five permanent magnet apparatuses, containing two permanent magnets made of Neodymium, the strongest

commercially available, created the magnetic fields [7]. Two types of Neodymium permanent magnets were utilized, N42 and N52, which are two magnetic grades [7]. The magnetic grade N52 produces more Tesla than the magnetic grade N42 [7]. Set up 1 contained two 1 inch by 1 inch N42 magnets, set up 2 contained two 1.5 inch by 1.5 inch N42 magnets, and set up 3 utilized two 2 inch by 2 inch N42 magnets. Set up 4 contained two 1 inch by 1 inch N52 magnets, and set up five, two 2 inch by 2 inch N52 magnets. A USB compatible, USB digital microscope captured images of each suspended droplet. In front of the coil, a fan was placed to keep the temperature within the coil as close to ambient temperatures as possible. A Gauss meter measured the magnetic field strength within the coil at the height at which the needle was placed in the coil and in between the two permanent magnets for each apparatuses.

2.2 Materials for Magnetic Field induced by Solenoid Magnet

250 mL of the highest concentration for each surfactant was made and diluted to 50 mL for each diluted concentration using distilled water. The surfactants analyzed in the solenoid magnet were C-TACo ($C_{38}H_{84}N_2Br_2CoC_{l2}$) and C-TADy ($C_{19}H_{42}NBrDyC_{l3}$). These surfactants were synthesized from hexadecyltrimethylammonium bromide, which was purchased from *Sigma-Aldrich* (CAS 57-09-0). The cobalt (II) chloride ($ClCo_2{\cdot}6H_2O$) used to synthesize C-TACo was purchased from *Alfa Aesar* (CAS 7791-13-1). The dysprosium magnetic surfactant was already synthesized and in the laboratory. The concentrations for each surfactant measured are shown in Table 2-1.

Table 2-1. Magnetic Surfactant concentrations in parallel magnetic field.

Magnetic Surfactant	Concentrations Tested (mM)						
C-TACo	0.25	0.45	0.65	0.75	0.98	1.20	---
C-TADy	0.18	0.36	0.53	0.71	0.89	1.07	1.25

Methanol was used to clean all equipment and prevent contamination between uses.

2.3 Materials for Magnetic Field Induced by two Permanent Magnets

To dilute each surfactant, 250 mL of the highest concentration for each surfactant was made and diluted to 50 mL for each diluted concentration using distilled water. The surfactants analyzed in the parallel magnetic field were C-TAD$_y$, C-TAC$_O$, and C-TAB. These magnetic surfactants were synthesized from hexadecyltrimethylammonium bromide, which was purchased from *Sigma-Aldrich* (CAS 57-09-0). The cobalt (II) chloride ($ClCo_2 \cdot 6H_2O$) used to synthesize C-TACo was purchased from *Alfa Aesar* (CAS 7791-13-1). The dysprosium magnetic surfactant was already synthesized and in the laboratory. The concentrations for each surfactant measured is shown in Table 2-2.

Table 2-2. Magnetic surfactant concentrations analyzed in magnetic field induced by two permanent magnets.

Surfactant	Concentrations Tested (mM)						
C-TACo	0.25	0.45	0.65	0.75	0.98	1.20	---
C-TADy	0.18	0.36	0.53	0.71	0.89	1.07	1.25
C-TAB	0.25	0.45	0.65	0.75	0.95	---	---

Methanol was used to clean all equipment and prevent contamination between uses.

2.4 Procedure for diluting Surfactant Solutions

To dilute the surfactant solutions to the concentrations shown in Table 2-1 and Table 2-2, calculations were performed before data was taken. The total molecular weight of each surfactant was found by summing the molecular weights of the corresponding elements making up the surfactant. The moles of each solid surfactant needed for the highest concentrations was calculated for a 250 mL solution using Equation 2.1.

Equation 2.1 $$Molarity\ (M) = \frac{moles\ (mol)}{Volume\ (L)}$$

The mass of solid surfactant was found using Equation 2.2.

Equation 2.2 $$Mass\ (grams) = moles \times molecular\ weight$$

Once the mass of surfactant was determined, the fraction of the maximum concentration each solution needed for dilution was calculated. To find the volume (mL) of the maximum concentration for each diluted solution, Equation 2.3 was used.

Equation 2.3 $$Volume\ of\ Max\ Concentration = (fraction\ of\ Max\ concentration) \times (50\ mL)$$

For each of the diluted solutions, the volume of maximum concentration calculated was added to the 50 mL volumetric flasks using the 100 mL graduated cylinder and Finn Pipette. The remainder of the 50 mL volumetric flask was filled with distilled water. The volumetric flask was stirred lightly to evenly mix the concentrated surfactant with the diluted water.

2.5 Experimental Setup for Solenoid Magnet

To ensure that all the droplets were held at the same height and exposed to the same magnetic field strength in the coil, finger nail polish was used to mark where the clasps should be attached on the ring stand and to mark where the syringe should be placed on the clasps. A hole was drilled in the middle of the solenoid magnet in which the needle tip was placed. In order to keep the coil cool and maintain consistency in the droplets, a small fan blew in front of the coil, while data was taken. To obtain droplet pictures with good contrast that were easy to see and allowed for a more consistent analysis, a white backdrop with a lamp was also used. The experimental setup for the coil can be seen in Figure 2-1.

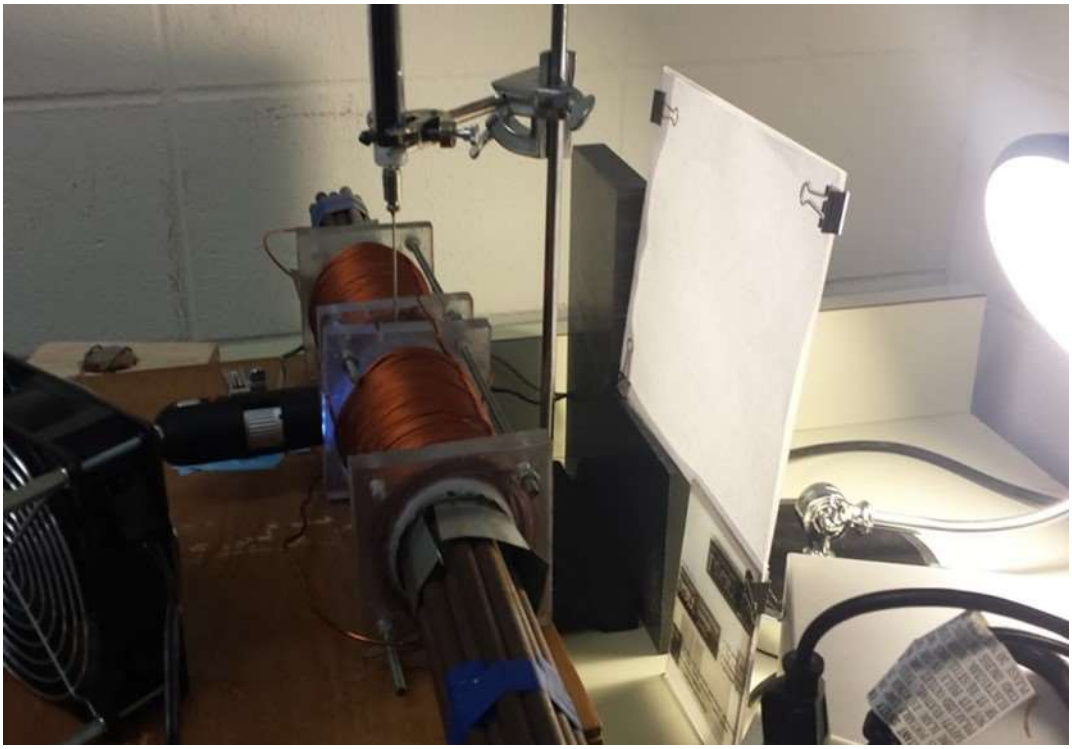

Figure 2-1. Experimental setup for a coil to create parallel magnetic field.

2.6 Procedure for Solenoid Magnet

The surfactant solutions were prepared for each magnetic surfactant at the desired concentrations and stored in 50 mL volumetric flasks covered with parafilm. The metal needle was covered with a glass capillary tube and held in place with vacuum grease, which prevented interference with the magnetic field. The needle and glass syringe were cleaned by drawing methanol through the needle and into the syringe and then purging the syringe. The stopper and glass syringe were separated and paper towel dried. The dried glass syringe and stopper were put back together. The magnetic surfactant was transferred from the 50 mL volumetric flask to a small vial, which allowed the magnetic surfactant to be drawn by the needle due to the needle not being long enough to reach the solution in the 50 mL volumetric flask. The magnetic surfactant was drawn through the needle and into the glass syringe, and the magnetic surfactant was then purged. This was repeated twice for each new magnetic surfactant concentration to ensure that no contamination occurred

in the syringe and needle. The magnetic surfactant was drawn into the syringe for a third time to be placed into the coil. Before placing the needle into the coil, the syringe was turned 180 degrees and lightly tapped to bring air bubbles to the base of the syringe. Air bubbles were expelled out of the syringe to reduce the frequency of air bubbles in the droplets. Once air bubbles were removed, the needle tip was wiped with Kimwipes®, which had been soaked with methanol; this ensured that the external needle tip was clean and prevented the surfactant solutions from adhering to the sided of the needle. The needle tip was then placed into the magnetic coil, and the syringe was held in place using clasps attached to the stand placed above the coil. The drops were captured for 0 A, 5 A, 10 A, 15 A, and 19.5 A currents running through the coil whose Tesla values can be found in Table 3-1, and three droplets were captured for each magnetic surfactant concentration and current. Instead of using a 20 A current, a 19.5 A current was used to prevent a fuse from blowing and for safety precautions in the laboratory. Images were not captured if the droplets shook vigorously, contained air bubbles, or adhered to the tip of the needle, and a new droplet was made to eliminate these droplet imperfections.

2.7 Experimental Setup for Two Permanent Magnets

To ensure that all the droplets were held at the same height and exposed to the same magnetic field strength in the coil, finger nail polish marked where the clasps should be attached on the ring stand and where the syringe should be placed on the clasps. A hole was made in between the plates, keeping the permanent magnets in place. This hole allowed for the needle tip to be dropped in between the two permanent magnets and the droplet to be exposed to the two magnets. Two holes were drilled into a table, and the permanent magnet apparatus was anchored into place with nuts and bolts, allowing the

magnets to be changed when necessary. A block of wood was taped to the edge of the ring stand, and a microscopic camera was taped to the table, so it would remain in front of the permanent magnets. A white backdrop with a lamp was also utilized to obtain droplet pictures with good contrast, which allowed for a more consistent analysis. The arrangement for this set up is shown in Figure 2-2, and the apparatus used to keep the two permanent magnets in place is shown in Figure 2-3.

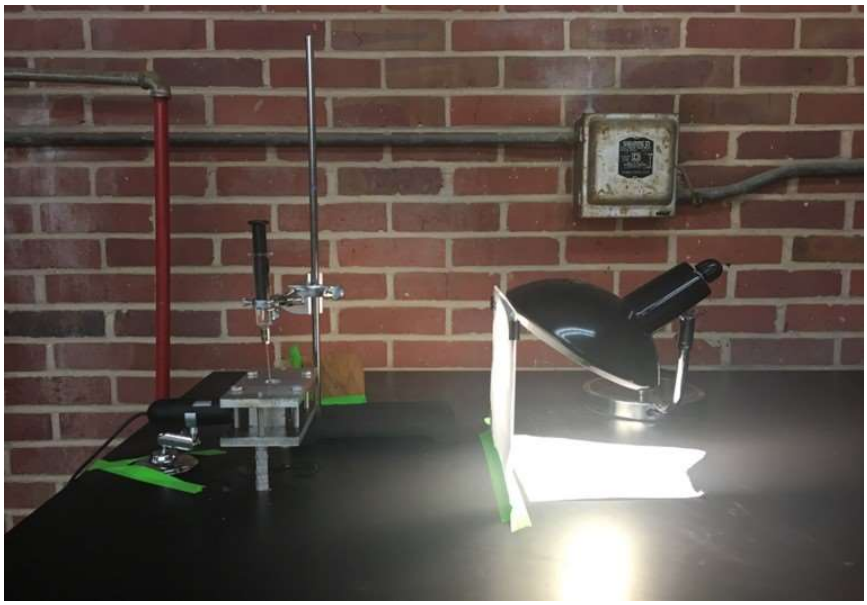

Figure 2-2. Experimental setup for two permanent magnets.

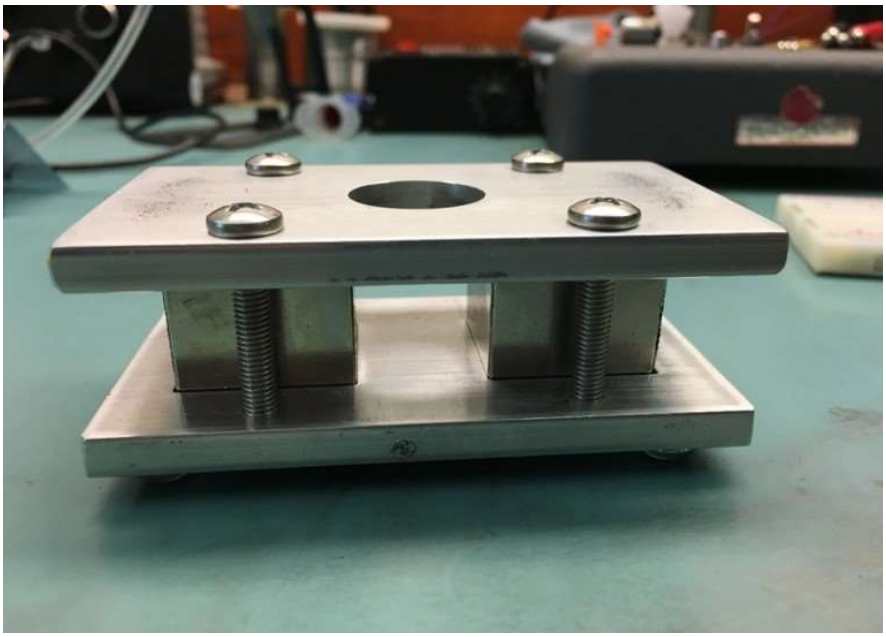

Figure 2-3. Apparatus used for placement of permanent magnets.

2.8 Procedure for two Permanent Magnets

The surfactant solutions were prepared for each magnetic surfactant at the desired concentrations and stored in 50 mL volumetric flasks with parafilm covers. The needle and glass syringe were cleaned by drawing methanol through the needle and into the syringe and then purging the syringe of methanol. The stopper and glass syringe were separated and paper towel dried. The dried glass syringe and stopper were put back together. The magnetic surfactant was poured from the 50 mL volumetric flask to a small vial, which allowed the magnetic surfactant to be drawn by the needle. The end of the needle was not long enough to reach the solution in the 50 mL volumetric flask. The magnetic surfactant was drawn through the needle and into the glass syringe, and then, the magnetic surfactant was purged. This was repeated twice for each new magnetic surfactant concentration to ensure no contamination in the syringe and needle. The magnetic surfactant was drawn into the syringe for a third time to be placed into the coil. Before placing the needle into the coil, the syringe was lightly shaken to bring air bubbles to the

base of the syringe. Air bubbles were expelled out of the syringe to reduce the number of air bubbles in the droplets while the needle was in the coil. Once air bubbles were removed, the needle tip was placed between the permanent magnets, and the syringe was held in place using clasps attached to the stand placed above the permanent magnets. Three droplets were captured for each concentration of the magnetic surfactants.

3 RESULTS AND DISCUSSION

3.1 Surface Tension for Magnetic Surfactants in a Solenoid Magnet

Using a Gauss meter, the magnetic field strength inside the coil was manually found in the laboratory. The Tesla values for the corresponding currents running through the coil are shown in Table 3-1.

Table 3-1. Solenoid magnet field strength.

Current (A)	Magnetic Field Strength (T)
0.0	0.008
5.0	0.085
10.0	0.159
15.0	0.228
19.5	0.282

Data was taken for both C-TADy and C-TACo inside the solenoid magnet. For each of the currents running through the solenoid magnet, the surface tension values of C-TADy and C-TACo are shown in Table 3-2 and Table 3-3, respectively.

Table 3-2. Surface tension values for C-TADy

	Surface Tension (mN/m)				
Concentration (mM)	0.0 Amp	5.0 Amp	10.0 Amp	15.0 Amp	19.5 Amp
0.25	51.54	52.99	46.48	47.88	50.42
0.45	41.34	44.08	44.67	44.59	42.22
0.65	32.58	36.19	37.06	34.21	37.58
0.75	33.74	32.10	33.84	32.28	30.17
0.98	37.03	32.77	31.05	30.44	30.50
1.20	29.50	31.14	30.38	31.27	30.35
1.25	30.63	31.03	30.30	32.10	31.62

Table 3-3. Surface tension values for C-TACo.

Surface Tension (mN/m)					
Concentration (mM)	0.0 Amp	5.0 Amp	10.0 Amp	15.0 Amp	19.5 Amp
0.25	42.12	44.27	50.46	50.35	49.78
0.45	34.13	33.41	35.36	35.70	35.11
0.65	31.11	31.44	34.03	34.01	32.45
0.75	31.23	32.98	35.30	32.23	33.42
0.98	30.88	30.45	33.15	31.49	32.95
1.20	31.57	30.10	34.20	31.56	31.49

Based on the hypothesis, the surface tension values in Table 3-2 and Table 3-3 should decrease from top to bottom as the concentration increases, and the surface tension values should decrease from left to right as the magnetic field strength increases. Although these general trends were seen, the trends were not seen explicitly for all values in Table 3-2 and Table 3-3. The numerical values for surface tension were plotted against concentration and are represented in Figure 3-1 and Figure 3-2.

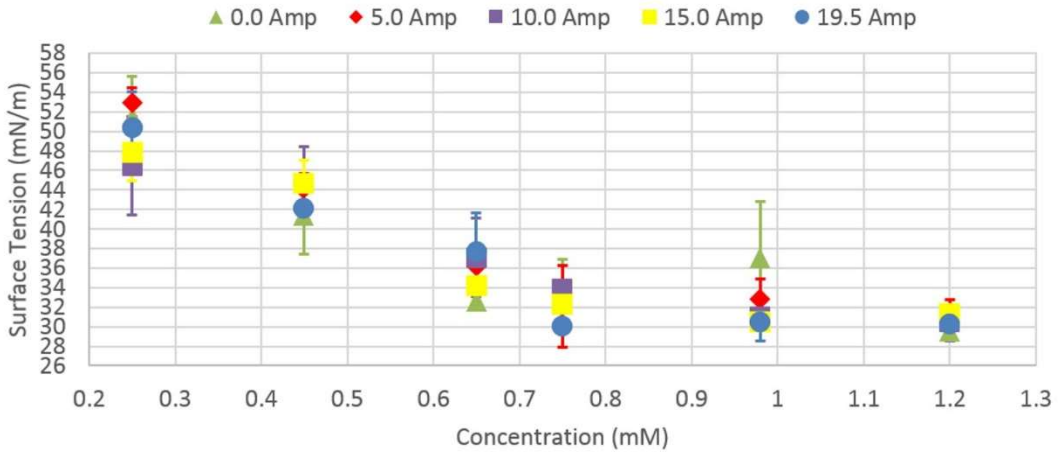

Figure 3-1. Surface tension values for C-TADy exposed to solenoid magnet. Surface tension values for C-TADy exposed to the solenoid magnet as concentration increases at varying magnetic field strengths.

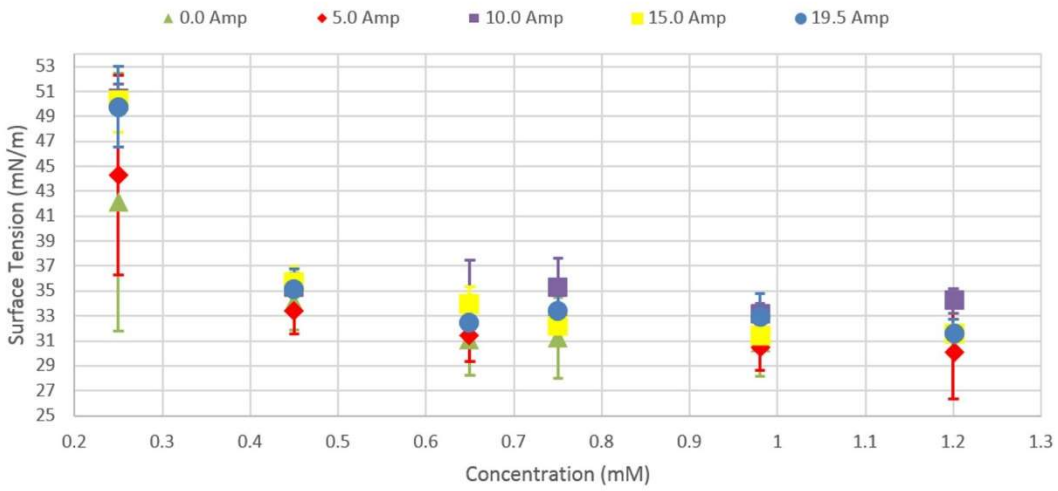

Figure 3-2. Surface tension values for C-TACo exposed to solenoid magnet. Surface tension values for C-TACo exposed to the solenoid magnet as concentration increases at varying magnetic field strengths.

To easily see the trends between surface tension and magnetic field strength, Figure 3-3 is shown below for the surface tension of C-TACo at no magnetic field and at one magnetic field strength. Graphs at each magnetic field strength of C-TADy and C-TACo can be found in the appendices.

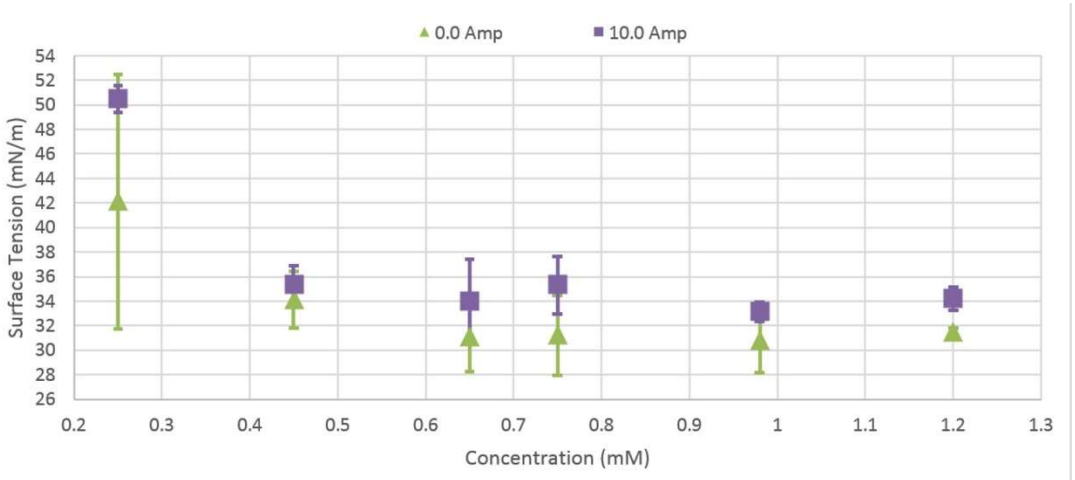

Figure 3-3. C-TACo surface tension with varied concentration and currents. Surface tension for varying concentration values of C-TACo at 0.0 Amp and 10.0 Amp running through the solenoid magnet.

As the concentration of the surfactant increases, the surface tension values should decrease, as there are more surfactant monomers available to adsorb onto the interface of the system.

If the hypothesis for this research was true, the surface tension should also decrease as the magnetic field strength, or the amount of amperes being sent through the coil, increases. Based on the trends shown in the graphs, the surface tension overall did decrease as the concentration of the surfactants decreased, but the graphs show a slight dip and rise in surface tension as the concentration increases. While some of the surface tension values did decrease as the magnetic field strength increased, the opposite trend was also seen, as shown in Figure 3-3.

3.2 Surface Tension for Magnetic Surfactants in between Two Permanent Magnets

Using a Gauss meter, the magnetic field strength of each permanent magnet apparatus was found manually in the laboratory. These results are shown in Table 3-4.

Table 3-4. Magnetic field strength for two permanent magnet apparatus.

Permanent Magnets	Magnetic Field Strength (T)
N42-1 in x 1 in	0.470-0.475
N42-1.5 in x 1.5 in	0.520-0.530
N42-2 in x 2 in	0.600-0.700
N52-1 in x 1 in	0.470-0.480
N52-2 in x 2 in	0.670-0.680

The surface tension was measured for the magnetic surfactants C-TADy and C-TACo in the two permanent magnet apparatuses. The surface tension of the control surfactant C-TAB was measured in the two permanent magnet apparatus as well. The numerical values of surface tension for each of the concentrations for the different magnetic apparatuses are shown in Table 3-5, Table 3-6, and Table 3-7, respectively.

Table 3-5. Surface tensions for C-TADy at varying concentrations and magnet apparatus.

	Surface Tension (mN/)					
Concentration (mM)	No Magnet	N42-1in x 1in	N42-1.5in x 1.5in	N42-2in x 2in	N52-1in x 1in	N52-2in x 2in
0.25	44.50	44.78	45.46	42.82	40.98	42.29
0.45	34.24	34.68	32.41	29.17	33.67	31.43
0.65	28.94	29.61	26.58	27.81	25.44	28.45
0.98	30.15	31.33	23.20	22.49	25.52	19.42
1.20	27.41	28.45	26.17	30.82	27.55	24.48
1.25	29.66	29.49	26.67	26.55	28.88	24.17

Table 3-6. Surface tensions for C-TACo at varying concentrations and magnet apparatus.

	Surface Tension (mN/m)					
Concentration (mM)	No Magnet	N42-1in x 1in	N42-1.5in x 1.5in	N42-2in x 2in	N52-1in x 1in	N52-2in x 2in
0.25	36.57	36.58	36.29	37.68	38.02	34.94
0.45	30.89	30.02	31.52	32.01	31.18	30.20
0.65	29.71	29.49	30.10	30.82	28.86	29.32
0.98	30.89	29.29	28.57	30.26	29.44	30.30
1.20	29.51	30.90	29.96	31.28	28.85	29.84
1.25	32.78	32.68	30.42	27.69	31.08	29.43

Table 3-7. Surface tensions for C-TAB at varying concentrations and magnet apparatus.

	Surface Tension (mN/m)					
Concentration (mM)	No Magnet	N42-1in x 1in	N42-1.5in x 1.5in	N42-2in x 2in	N52-1in x 1in	N52-2in x 2in
0.25	47.83	46.07	45.56	48.22	48.33	42.19
0.45	37.44	38.50	37.91	37.53	38.60	35.48
0.65	33.16	31.47	31.86	30.89	31.44	31.87
0.75	29.67	32.92	30.51	30.40	29.94	31.26
0.95	28.28	28.50	30.72	30.99	30.54	26.80

As with the solenoid magnet, if the hypothesis is true, the surface tension values in Table 3-6 and Table 3-7 should decrease from top to bottom as the concentration increases, and the surface tension values should decrease from left to right as the magnetic field strength increases. Although these general trends were seen, the trends again were not seen explicitly for all values in Table 3-6 and Table 3-7. The numerical values for surface tension were plotted against concentration for C-TADy and C-TACo and are represented

graphically in Figure 3-4 and Figure 3-6, respectively. To easily see the trends between surface tension and magnetic field strength, graphs, Figure 3-5 and Figure 3-7, are shown for C-TADy and C-TACo surfactants, respectively, atone magnetic field strength and with no magnet. Graphs for each individual magnetic field strength compared to no magnetic field can be found for all the magnetic surfactants in the appendices.

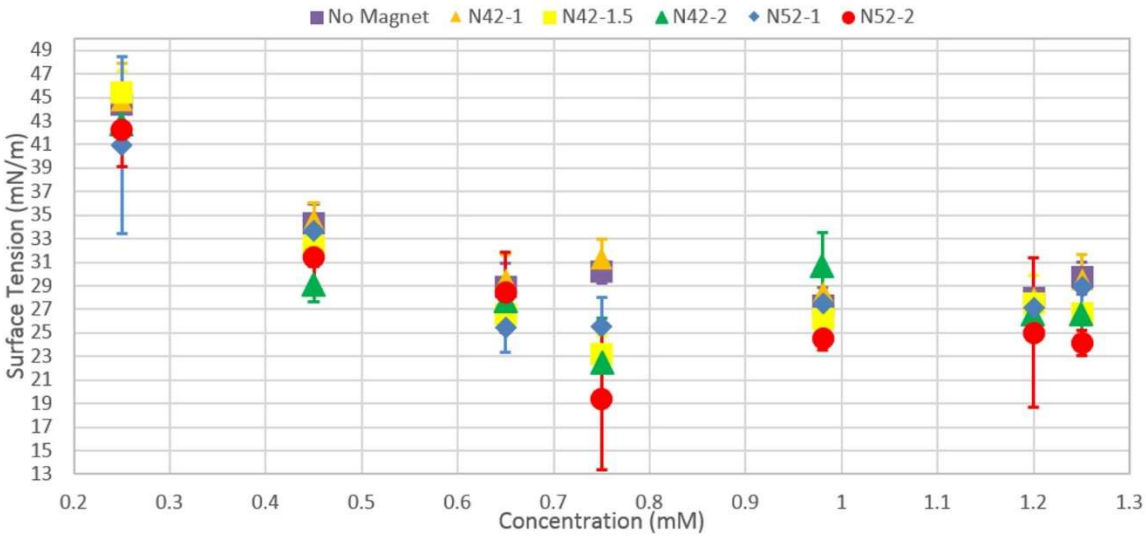

Figure 3-4. C-TADy surface tension at varying concentration and permanent magnet apparatus.

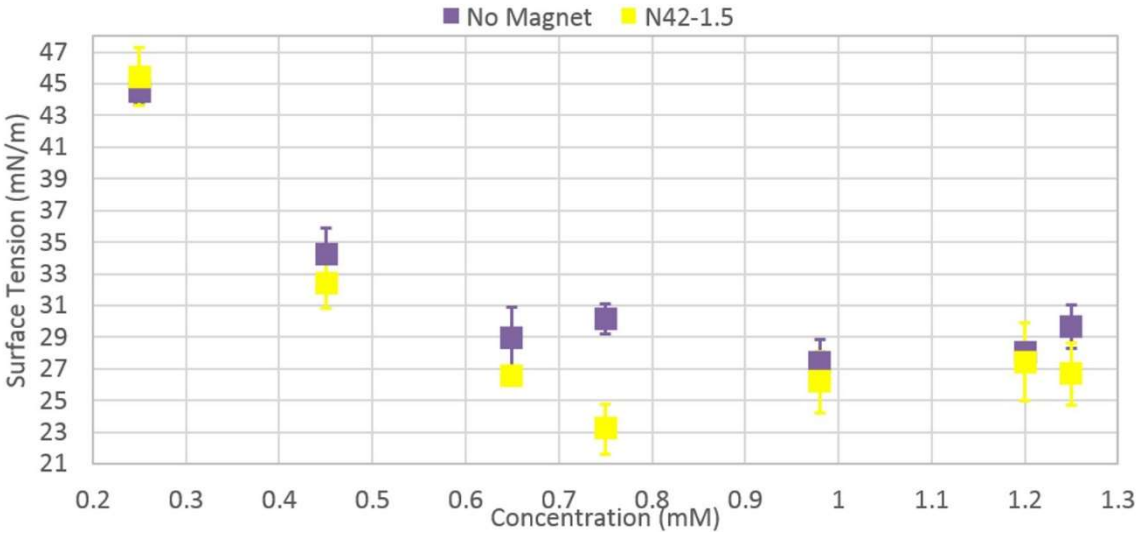

Figure 3-5. C-TADy surface tension at varying concentrations for no magnet and N42-1.5in x 1.5in magnets.

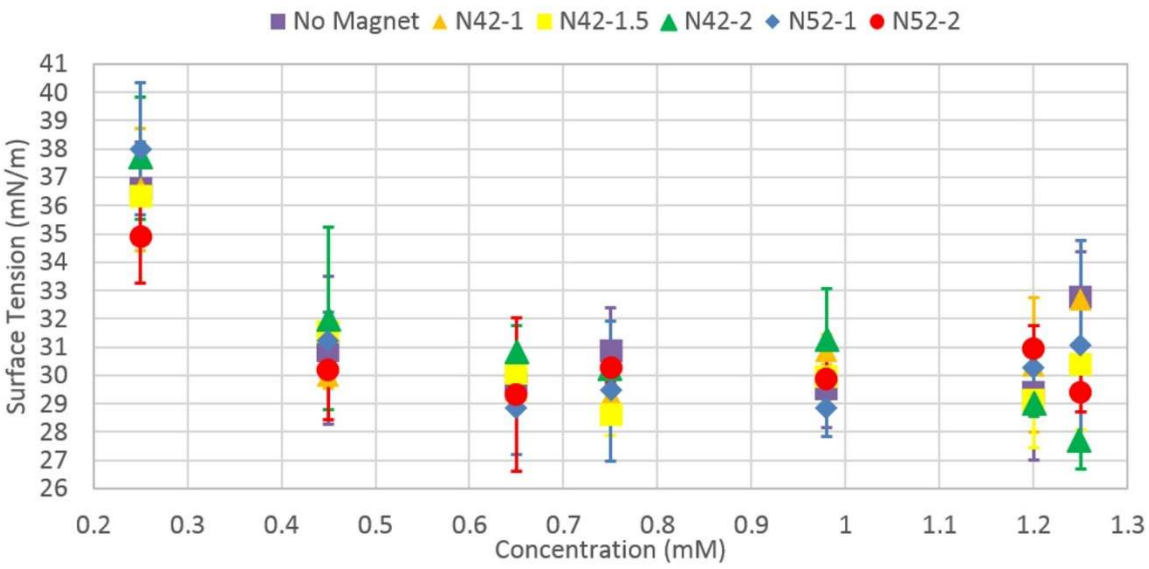

Figure 3-6. C-TACo surface tension at varying concentrations and permanent magnet apparatus.

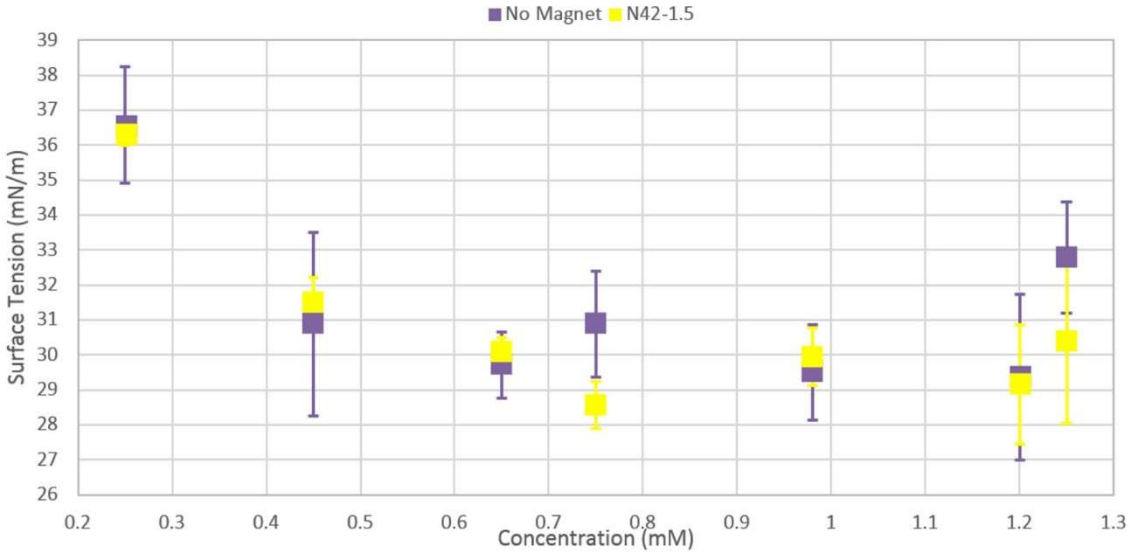

Figure 3-7. C-TACo surface tension as concentration increases for no magnet and N42-1.5in x 1.5in magnets.

For each of the graphs for surface tension as a function of concentration at varying magnetic field strengths, it can be seen that the surface tension decreases as the concentration of the solution increases. Based on literature, this is consistent with the trends for surface tension as concentration increases. [8] As the concentration of the surfactant increases, more surfactant monomers are present in the system, meaning there

are more surfactant monomers present to adsorb on the system's interface and disrupt the hydrogen bonding that creates the interfacial tension. However, in Figure 3-1 through Figure 3-7, it can be seen that there is a slight dip and rise in surface tension as the concentration increases. This trend is indicative of impure surfactant solutions as seen in Figure 3-8.

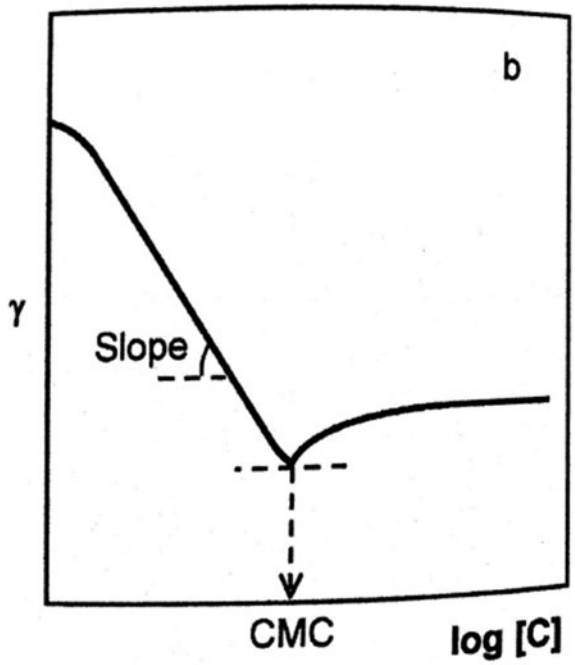

Figure 3-8. Surface tension slight dip and rise as concentration increases due to impure surfactants [8].

Often, impurities in surfactant solutions are other surfactant monomers. These impure, surfactant monomers can have hydrophobic chains that are as long as or longer than the main surfactant of the system. Before the CMC value is reached, these surfactant impurities will adsorb at the interface of the system, and the surface tension will decrease. Once the CMC for the main surfactant in the system is reached, the impurities will aggregate toward the micelle formation to decrease energy and increase entropy. As a result of this, the plateau seen past the CMC is more than likely the surface tension value from only the pure surfactant monomers at the interface. For C-TADy, the trend followed

the hypothesis as the surface tension trend decreased for the N42-2inch by 2inch apparatus compared to the no magnet setup, seen in Figure 3-5. For C-TACo, the trend was difficult to decipher as the surface tension was lower and higher for some values when the surfactant was placed in the N42- 2in by 2 in apparatus compared to the no magnet setup, seen in Figure 3-9.

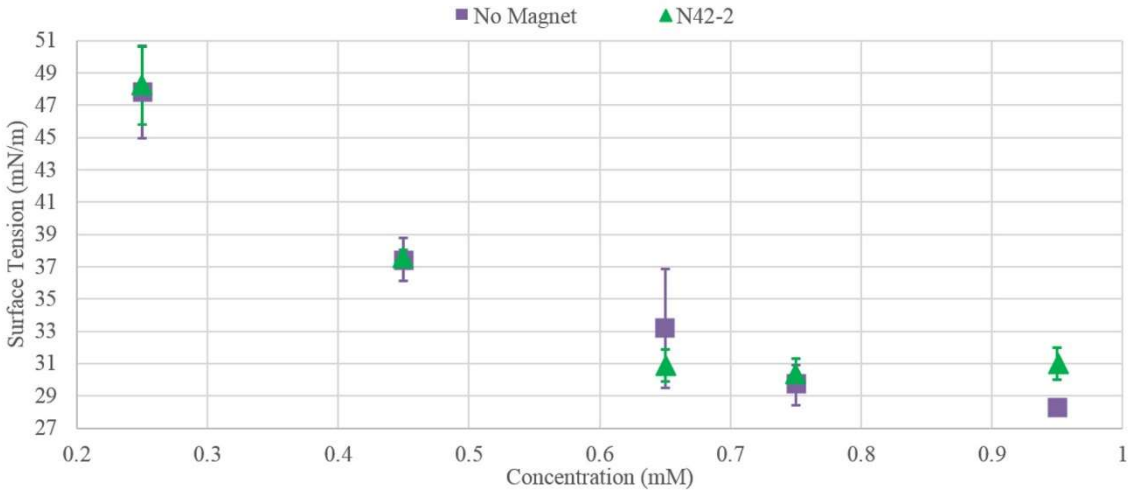

Figure 3-9. C-TAB surface tension at varying concentrations and permanent magnet apparatus.

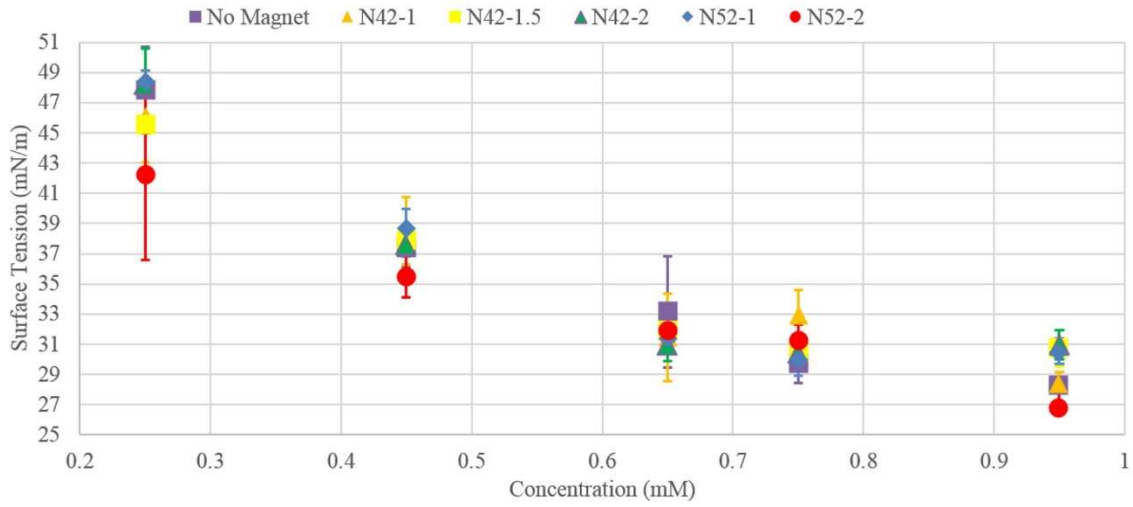

Figure 3-10. C-TAB surface tension as concentration increases for no magnet and N42-2in x 2in magnets.

Seen in Figure 3-10, the control surfactant C-TAB followed the general trend for surfactants like the magnetic surfactants because the surface tension decreased as the

concentration increased. The slight dip and rise trend in surface tension was not as clearly seen for the C-TAB as compared to the magnetic surfactants. This may be due to the fact that the C-TAB was from a stock solution in the laboratory and supplied by a manufacturer, while the magnetic surfactants were synthesized in the laboratory, where they had more opportunity to become contaminated. Since C-TAB has no magnetic properties, it would be expected that the surface tension for C-TAB inside and outside of the magnetic field is the same. For almost all of the data for C-TAB, there was no surface tension change for inside and outside of the magnetic field.

4 CONCLUSION AND FUTURE WORK

Although it was difficult to see a consistent trend for a decrease or increase in surface tension as the magnetic field strength increased, the surface tension values for the magnetic surfactants inside and outside of the magnetic field did vary, but inconsistently. For the C-TAB, the surface tension values did not vary at all inside and outside of the magnetic field. From this, it can be concluded that a change does occur to the magnetic surfactant monomers inside the magnetic field. It is still unclear, though, whether the change in surfactant monomers induced by the magnetic field results in an increase or decrease in surface tension. In order to find a more consistent trend for surface tension and magnetic field strength, more data in the laboratory would need to be taken. For each of the surface tension values shown in Tables 3-1 through 3-7, Figures 3-1 through 3-7, and both Figures 3-9 and 3-10, three separate droplets were captured, analyzed, and their surface tension values were averaged together. As seen by large standard deviations, some of the droplet's surface tension values varied greatly from the other two droplet's surface tension values, and these outlier values could have skewed the trends. The deviation values for each surface tension value calculated can be found in Appendix 6. It would be beneficial to capture ten to fifteen droplets for each concentration tested; this will allow for outlier values to be thrown out and to see a clearer trend of the data. The impurities in the surfactant solutions could have also altered the trends and skewed the surface tension values as most impurities aggregate toward the interface before the CMC is reached. Since most impurities aggregate in the micelle formation after the CMC is reached, measuring the surface tension of solutions with higher concentrations past the CMC values can give

a better representation of the surface tension values of the pure surfactants and not the impurities. In the future, to ensure that the surface tension values are the result of the pure magnetic surfactant being tested and not the impurities, it is important to recrystallize the surfactants four to five times in the synthesis stage as opposed to only once. Also, for future research, it would be beneficial to measure exact CMC values in the laboratory for the magnetic surfactants; this will make deciphering the trends in surface tension easier. It would also be beneficial to map the magnetic field strength between the two permanent magnets in the apparatus, as the magnetic field strength is not likely constant in the entire area between the two magnets. This would give more accurate values of the magnetic field strengths to which the droplets were exposed to. Overall, by taking data on more droplets, using more purified surfactants, using higher concentrations of magnetic surfactants, and by mapping the magnetic field strength of the permanent magnet apparatus, a clearer trend should be visible in order to determine if there is an induced alignment of magnetic surfactants at the interface when magnetic surfactants are exposed to magnetic fields.

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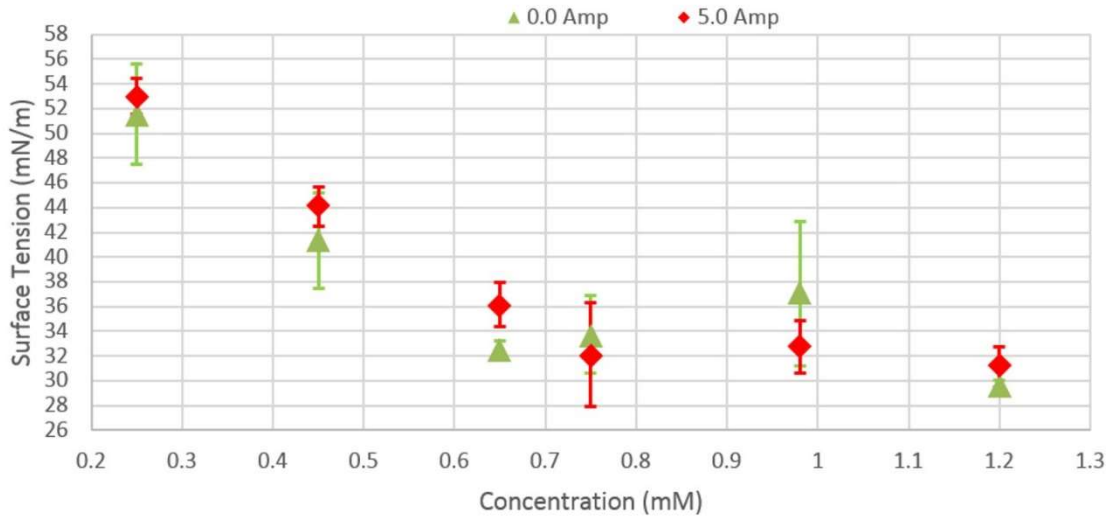
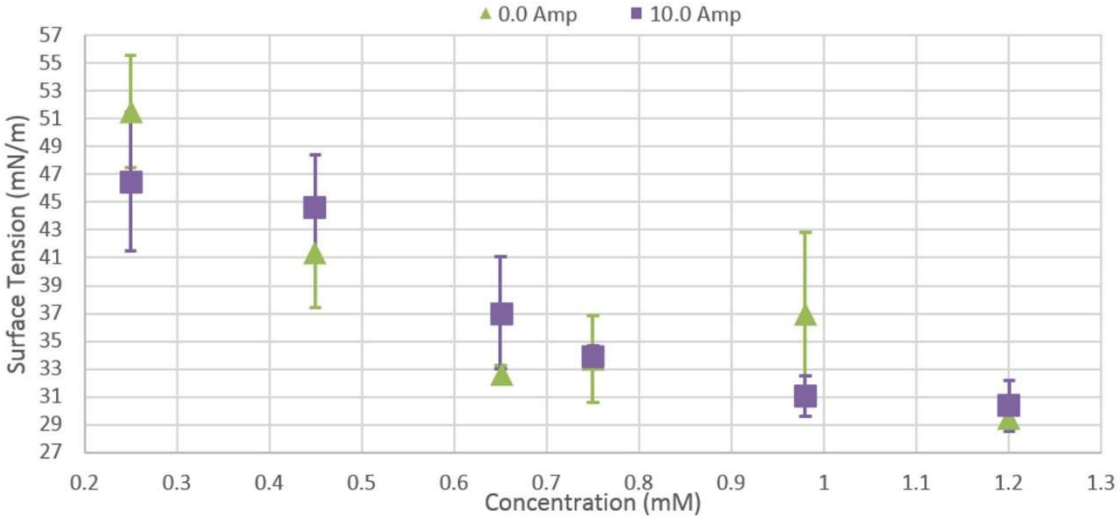
APPENDICES

APPENDIX 1

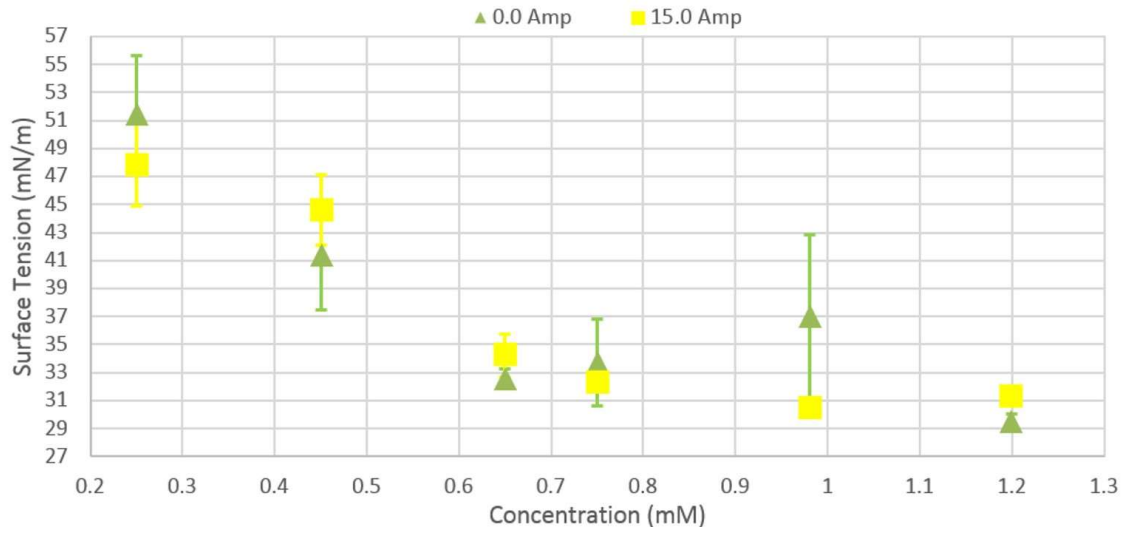
Appendix 1.1. Surface tension trend for C-TADy at varying concentrations for 0.0 Amp and 5.0 Amp running through solenoid magnet.



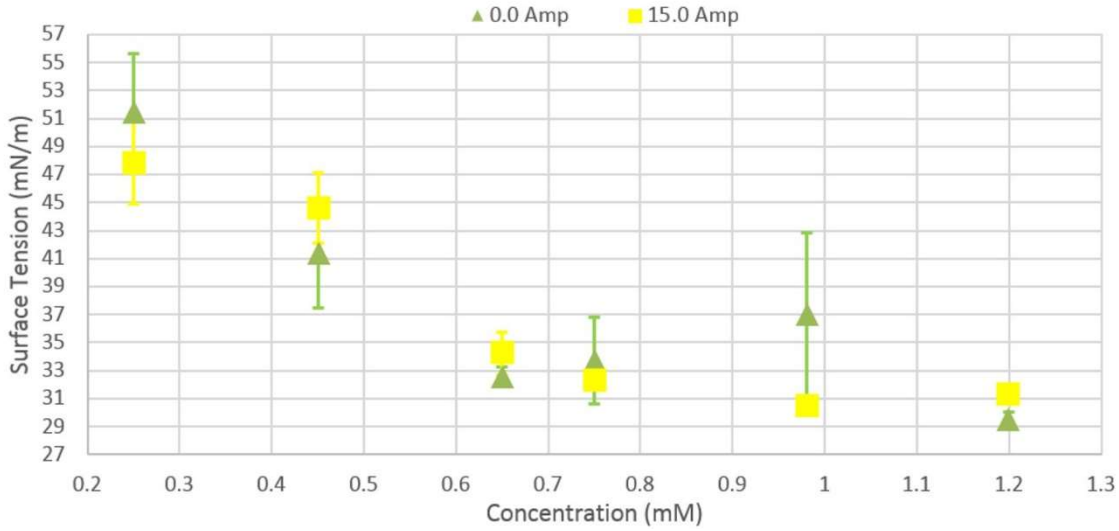
Appendix 1.2. Surface tension trend for C-TADy at varying concentrations for 0.0 Amp and 10.0 Amp running through solenoid magnet.



Appendix 1.3. Surface tension trend for C-TADy at varying concentrations for 0.0 Amp and 15.0 Amp running through solenoid magnet.

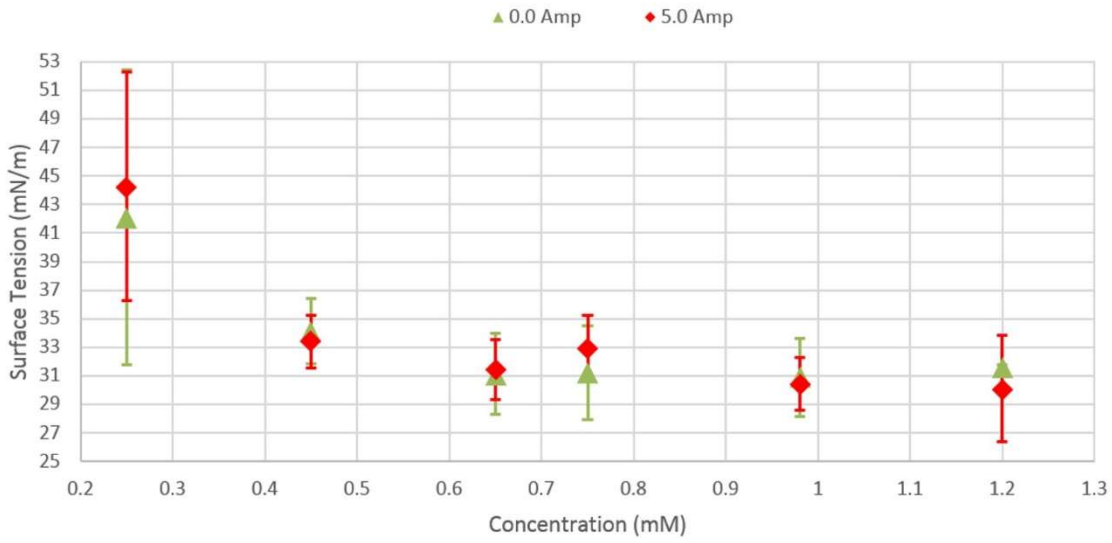


Appendix 1.4. Surface tension trend for C-TADy at varying concentrations for 0.0 Amp and 19.5 Amp running through solenoid magnet.

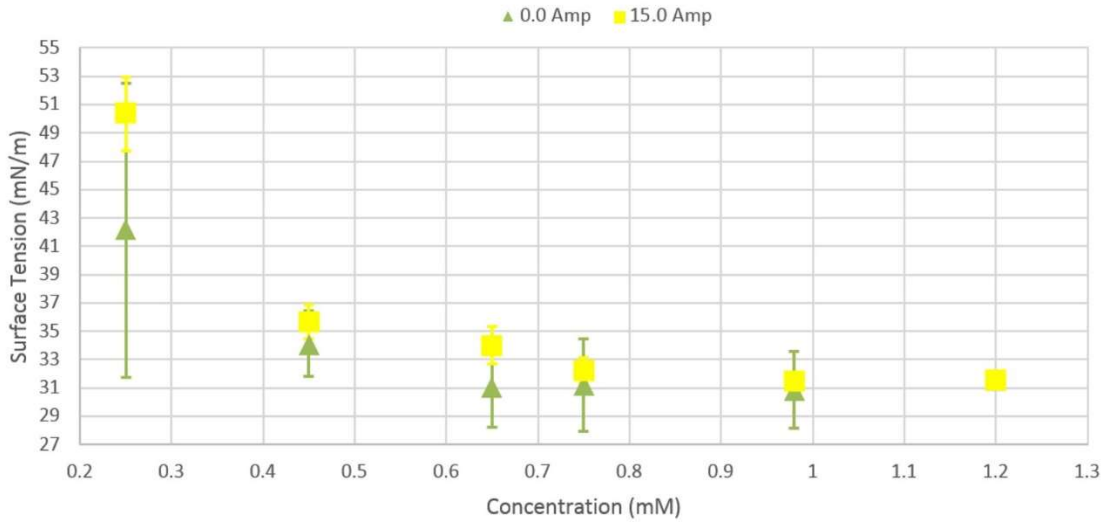


APPENDIX 2

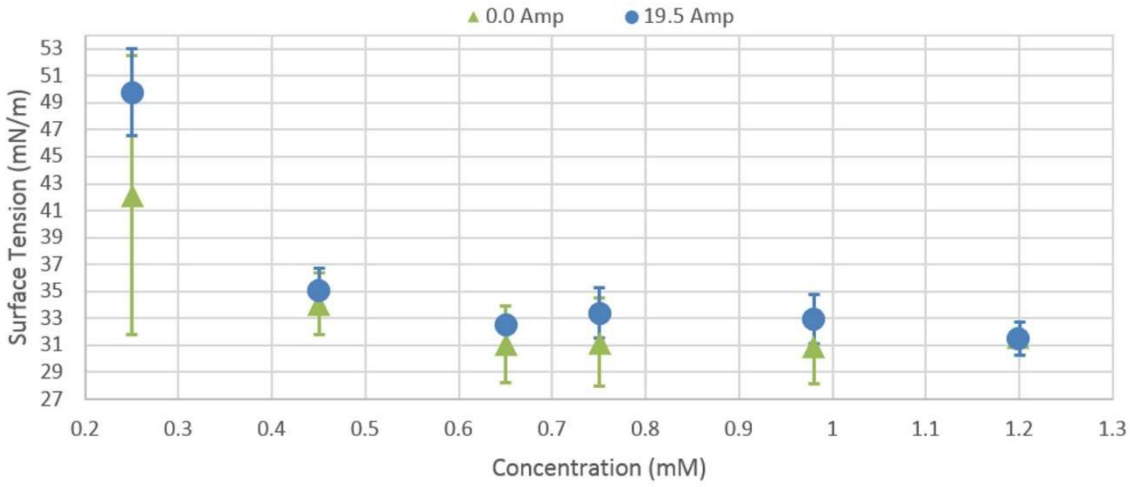
Appendix 2.1. Surface tension trend for C-TACo at varying concentrations for 0.0 Amp and 5.0 Amp running through solenoid magnet



Appendix 2.2. Surface tension trend for C-TACo at varying concentrations for 0.0 Amp and 15.0 Amp running through solenoid magnet.

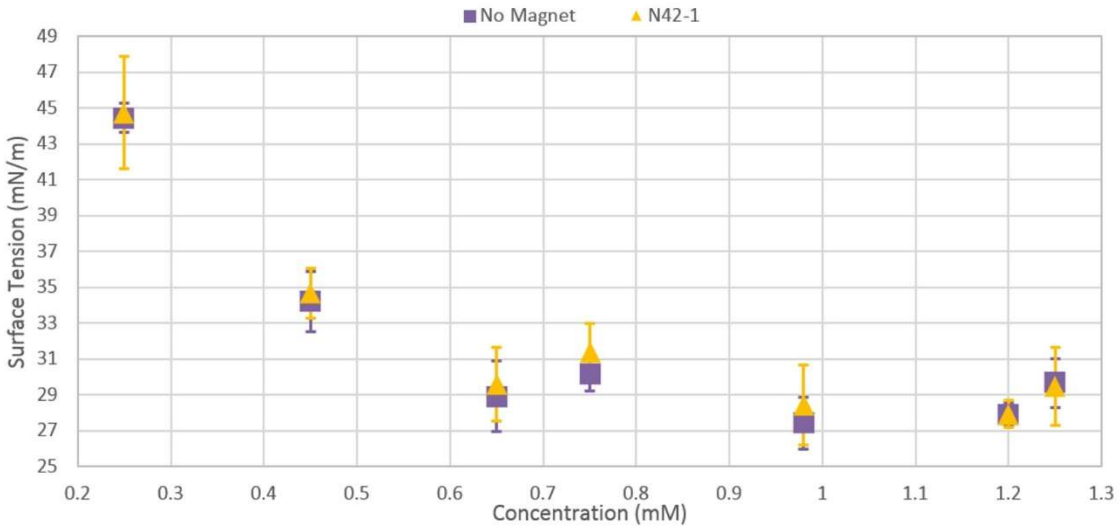


Appendix 2.3. Surface tension trend for C-TACo at varying concentrations for 0.0 Amp and 19.5 Amp running through solenoid magnet.

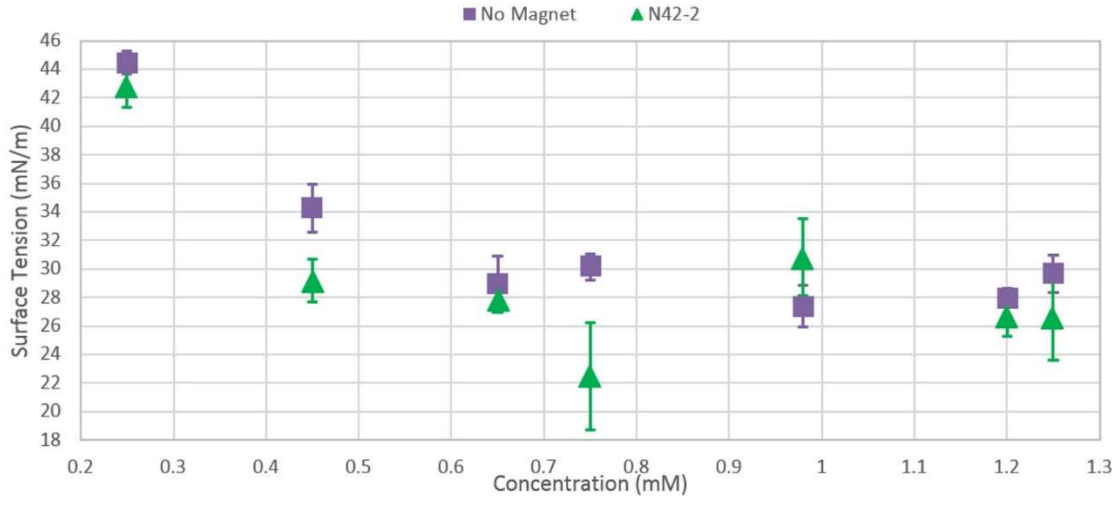


APPENDIX 3

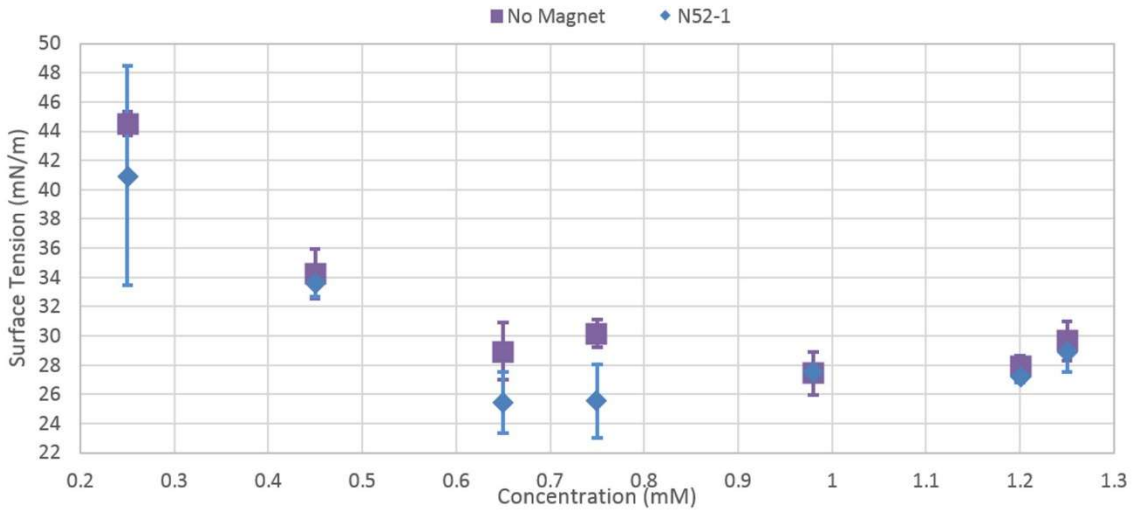
Appendix 3.1. Surface tension trend for C-TADy at varying concentrations for no magnet and N42-1in x 1in permanent magnets.



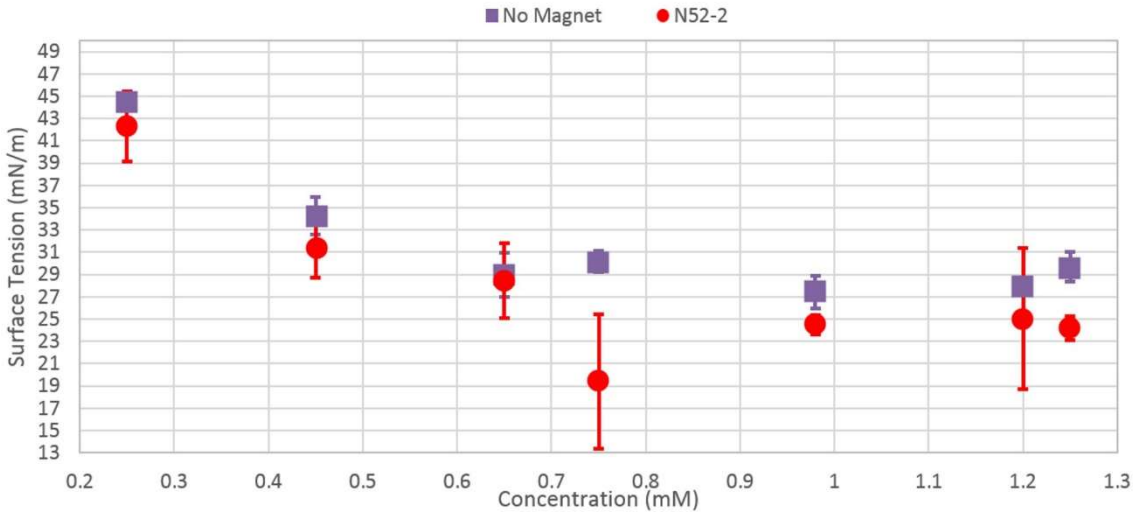
Appendix 3.2. Surface tension trend for C-TADy at varying concentrations for no magnet and N42-2in x 2in permanent magnets.



Appendix 3.3. Surface tension trend for C-TADy at varying concentrations for no magnet and N52-1in x 1in permanent magnets.

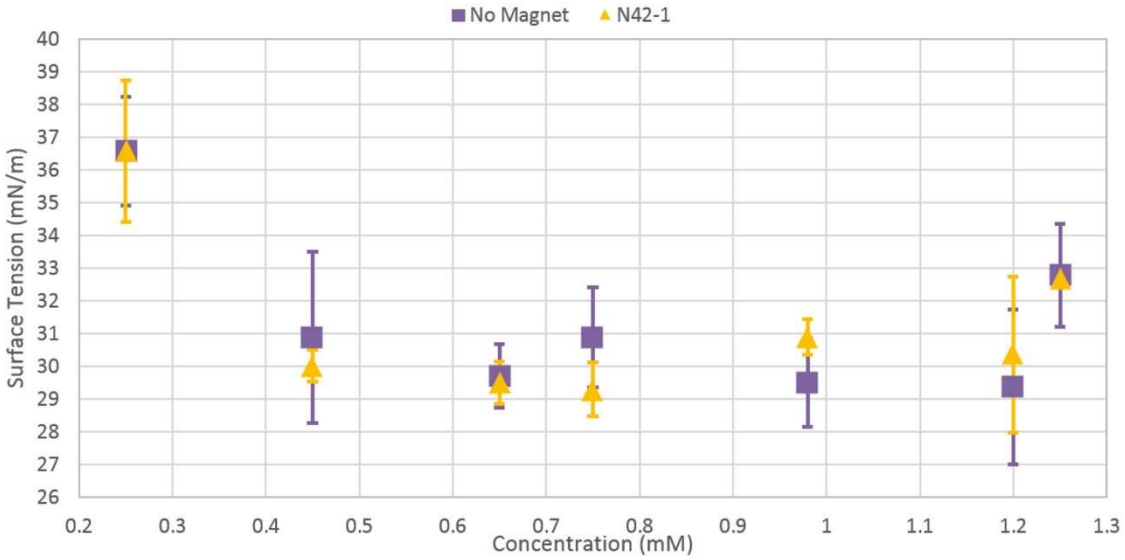


Appendix 3.4. Surface tension trend for C-TADy at varying concentrations for no magnet and N52- 2in x 2in permanent magnets.

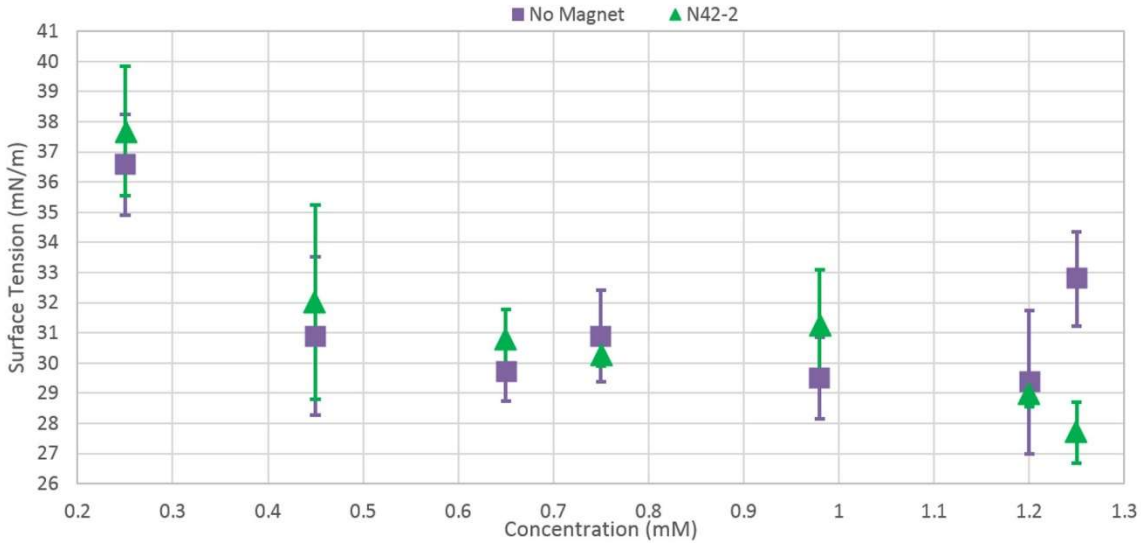


APPENDIX 4

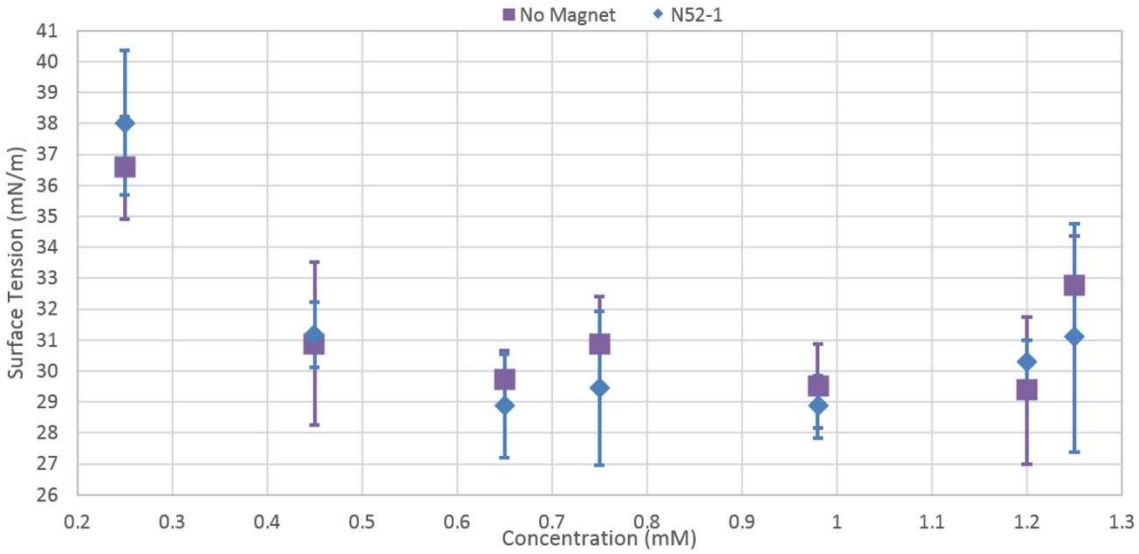
Appendix 4.1. Surface tension trend for C-TACo at varying concentrations for no magnet and N42-1in x 1in permanent magnets.



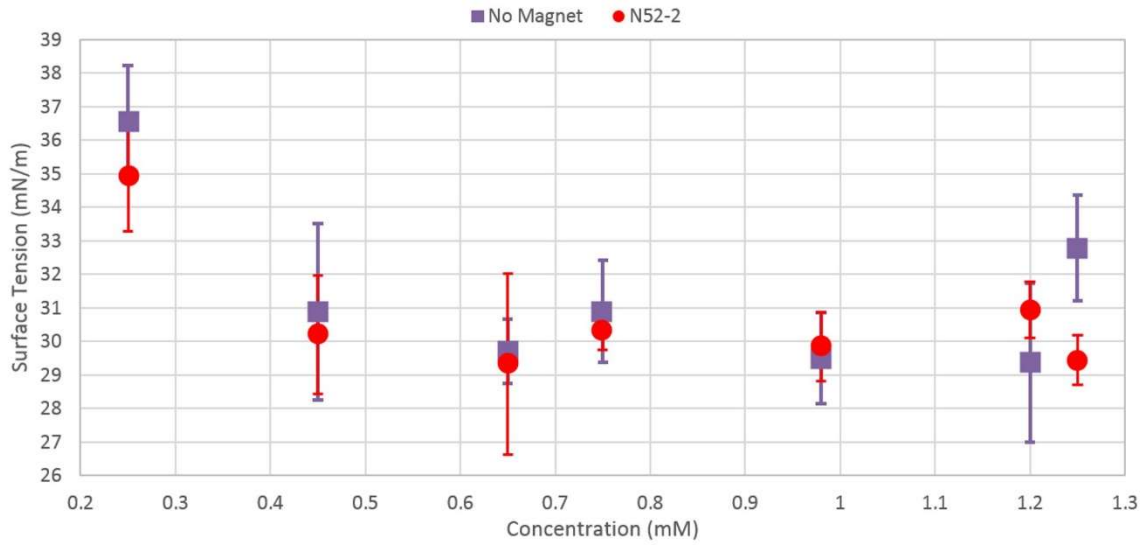
Appendix 4.2. Surface tension trend for C-TACo at varying concentrations for no magnet and N42-2in x 2in permanent magnets.



Appendix 4.3. Surface tension trend for C-TACo at varying concentrations for no magnet and N52-1in x 1in permanent magnets.

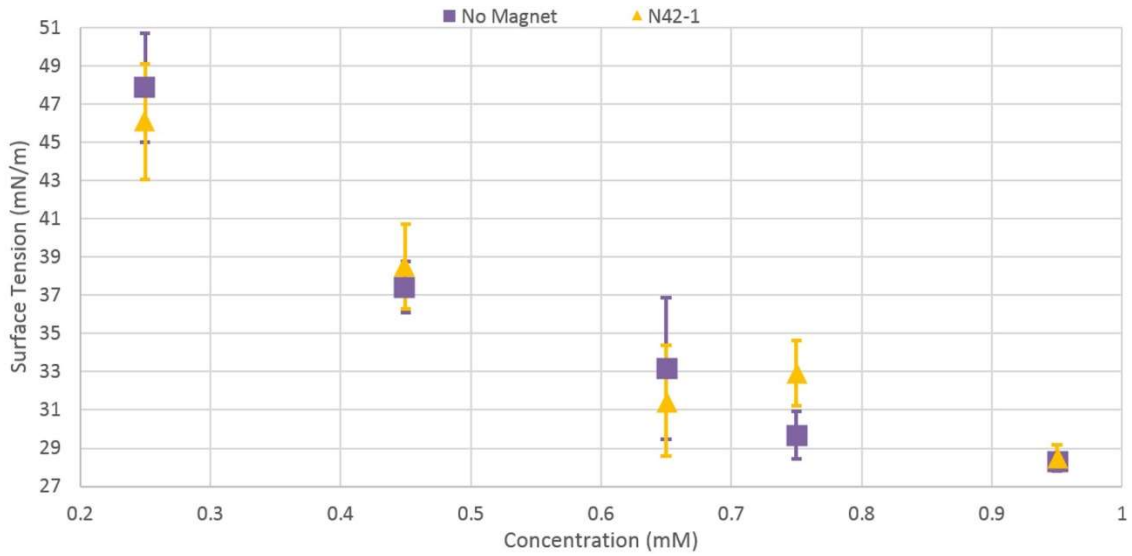


Appendix 4.4. Surface tension trend for C-TACo at varying concentrations for no magnet and N52- 2in x 2in permanent magnets.

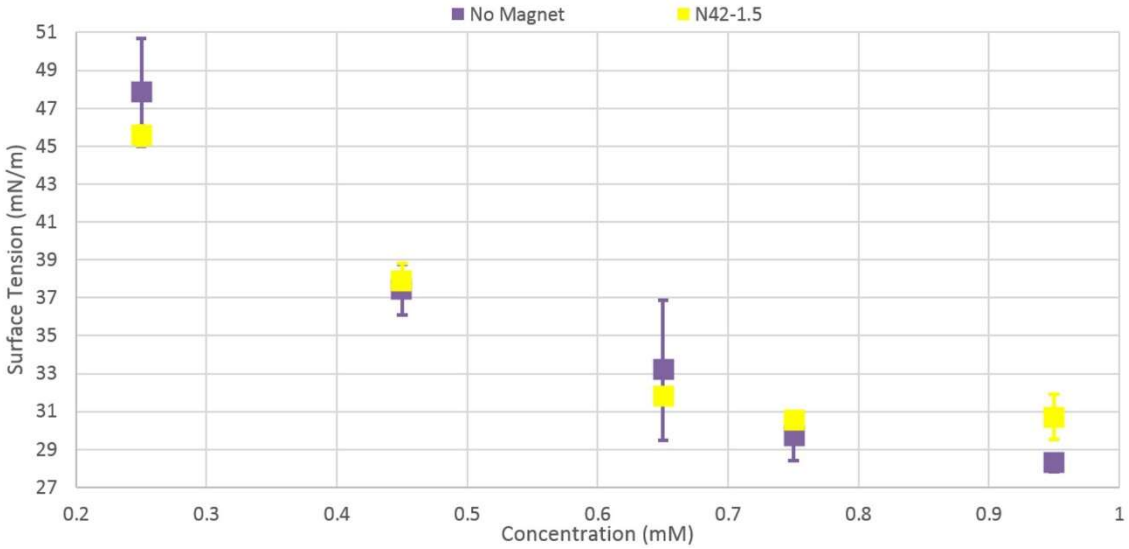


APPENDIX 5

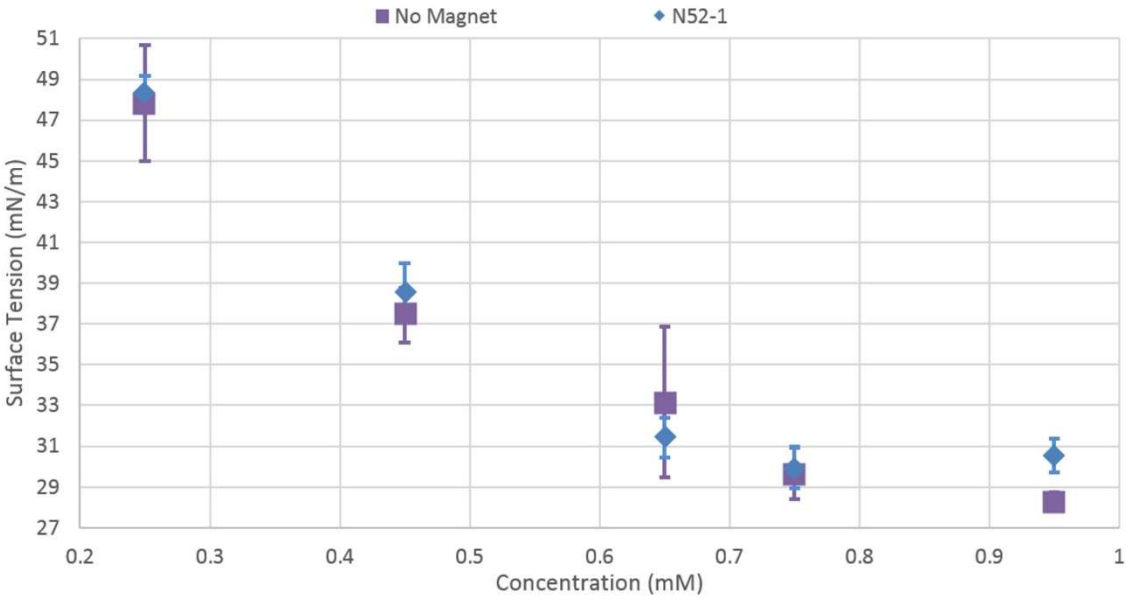
Appendix 5.1. Surface tension trend for C-TAB at varying concentrations for no magnet and N42-1in x 1in permanent magnets.



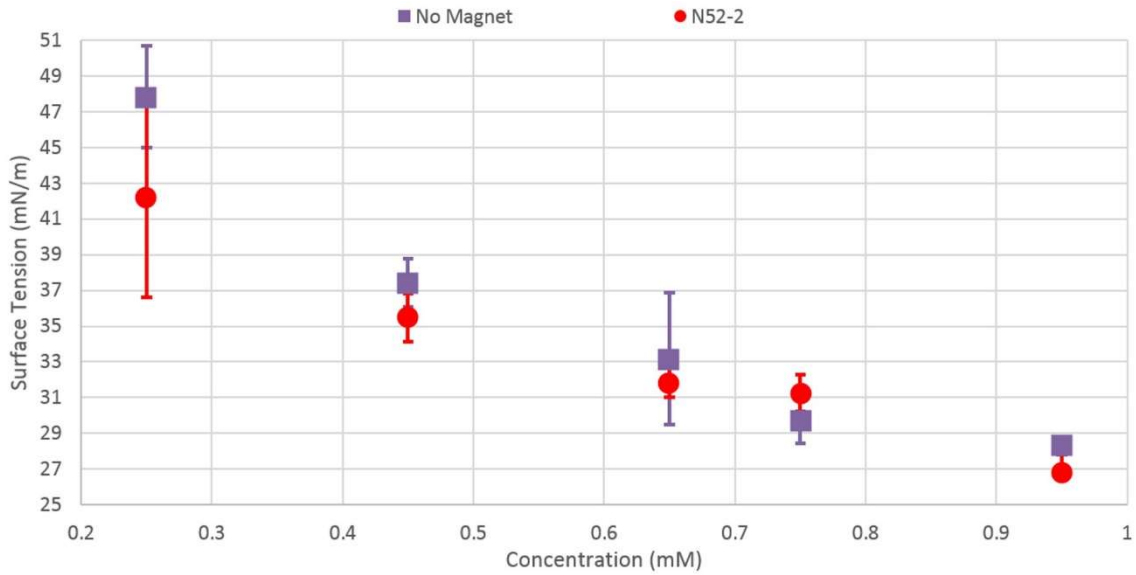
Appendix 5.2. Surface tension trend for C-TAB at varying concentrations for no magnet and N42-1.5in x 1.5in permanent magnets.



Appendix 5.3. Surface tension trend for C-TAB at varying concentrations for no magnet and N52-1in x 1in permanent magnets.



Appendix 5.4. Surface Tension Trend for C-TAB at varying concentrations for No Magnet and N52- 2in x 2in permanent magnets.



APPENDIX 6

Appendix 6.1. Error values for C-TADy in solenoid magnet based on standard deviation.

Current	0.0 A	5.0 A	10.0 A	15.0 A	19.5 A
Concentration (mM)	Error (mN/m)	Error (mN/m)	Error (mN/m)	Error (mN/m)	Error (mN/m)
0.18	4.05	1.47	4.99	2.98	3.64
0.36	3.88	1.56	3.77	2.51	1.75
0.53	0.66	1.81	4.02	1.50	4.05
0.71	3.11	4.17	0.84	0.30	0.62
0.89	5.81	2.13	1.46	0.18	1.96
1.07	0.56	1.63	1.82	0.40	0.77
1.25	0.72	0.23	1.01	0.98	1.71

Appendix 6.2. Error values for C-TACo in solenoid magnet based on standard deviation.

Current	0.0 A	5.0 A	10.0 A	15.0 A	19.5 A
Concentration (mM)	Error (mN/m)	Error (mN/m)	Error (mN/m)	Error (mN/m)	Error (mN/m)
0.25	10.35	8.00	1.12	2.63	3.24
0.45	2.30	1.84	1.52	1.22	1.62
0.65	2.84	2.09	3.41	1.30	0.24
0.75	3.26	2.23	2.34	0.94	1.88
0.98	2.72	1.84	0.81	0.23	1.84
1.20	0.23	3.75	0.97	0.48	1.24

Appendix 6.3. Error values for C-TADy between two permanent magnets based on standard deviation.

	No Magnet	N42- 1in x 1in	N42- 1.5in x 1.5in	N42- 2in x 2in	N52- 1in x 1in	N52- 2in x 2in
Concentration (mM)	Error (mN/m)	Error (mN/m)	Error (mN/m)	Error (mN/m)	Error (mN/m)	Error (mN/m)
0.18	0.81	3.12	1.80	1.48	7.51	3.13
0.36	1.68	1.39	1.55	1.50	0.99	2.68
0.53	1.97	2.04	0.25	0.82	2.08	3.37
0.71	0.93	1.64	1.59	3.76	2.50	6.03
0.89	1.45	2.22	1.93	2.73	0.31	0.89
1,07	0.64	0.74	2.46	1.36	0.34	6.35
1.25	1.35	2.19	1.97	2.93	1.36	1.06

Appendix 6.4. Error values for C-TACo between two permanent magnets based on standard deviation

	No Magnet	N42- 1in x 1in	N42- 1.5 in x 1.5in	N42- 2in x 2in	N52- 1in x 1in	N52- 2in x 2in
Concentration (mM)	Error (mN/m)	Error (mN/m)	Error (mN/m)	Error (mN/m)	Error (mN/m)	Error (mN/m)
0.25	1.66	2.16	0.30	2.14	2.34	1.67
0.45	2.62	0.49	0.70	3.22	1.06	1.76
0.65	0.96	0.65	0.39	0.95	1.67	2.69
0.75	1.52	0.83	0.67	0.36	2.48	0.56
0.95	1.36	0.55	0.82	1.80	1.02	1.04
1.20	2.37	2.38	1.71	0.46	0.70	0.83
1.50	1.58	0.00	2.36	1.01	3.70	0.74

Appendix 6.5. Error values for C-TAB between two permanent magnets based on standard deviation.

	No Magnet	N42- 1in x 1in	N42- 1.5in x 1.5in	N42- 2in x 2in	N52- 1in x 1in	N52- 2in x 2in
Concentration (mM)	Error (mN/m)	Error (mN/m)	Error (mN/m)	Error (mN/m)	Error (mN/m)	Error (mN/m)
0.25	2.85	3.00	0.52	2.39	0.82	5.60
0.45	1.34	2.24	0.88	0.51	1.36	1.35
0.65	3.69	2.89	0.39	0.99	0.97	0.82
0.75	1.25	1.69	0.44	0.92	1.02	1.04
0.95	0.47	0.66	1.20	0.97	0.84	1.42